MSW effect, oscillations and solar neutrinos

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8th Pontecorvo school , Sinaia, September 5, 2019

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Basics of oscillations in matter

The MSW effect in the Sun

Oscillations in the Earth

On Solar-KamLAND tension

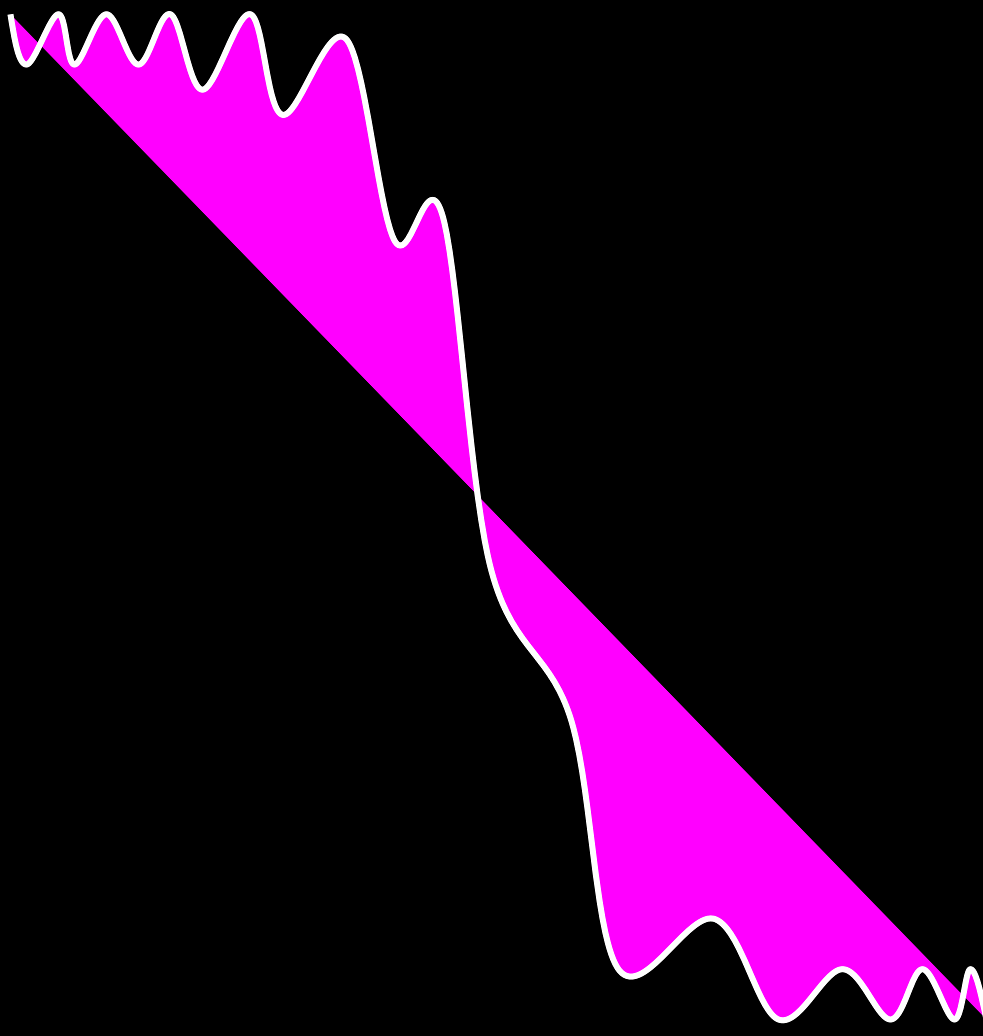
A. Yu. Smirnov, Solar neutrinos: Oscillations or No-oscillations?
arXiv:1609.02386 [hep-ph]

M. Maltoni, A Y. S. Solar neutrinos and neutrino physics. Eur.Phys.J. A52 (2016) no.4, 87. arXiv:1507.05287 [hep-ph]

A. Y. Smirnov, The MSW effect, solar neutrinos and searches for new physics. 2019. DOI: 10.1142/9789811204296_0007

A. Y. Smirnov, Solar neutrinos and matter effects. In "The state of the Art of Neutrino physics". World Scientific, 2018. p. 149 - 209

Basics of propagation in matter



Hamiltonian of propagation in vacuum

$$i \frac{d\,\nu_f}{d\,t} = H_0\, \nu_f$$

$$H_0 = \frac{M^+ M}{2E}$$

M is mass matrix in the flavor basis

Derivation

Mass states are eigenstates of propagation in vacuum

For single ultra relativistic mass state

$$H_1 = E \sim p + \frac{m^2}{2E}$$

For three mass states in the mass basis:

$$H_3 = EI \sim pI + \frac{1}{2E} \mathrm{diag}\,(m_1^2\,, m_2^2\,,\ m_3^2\,)$$

I is unit matrix

pI can be omitted

In the flavor basis using relation $\nu_f = U_{PMNS}\, \nu_{mass}$

$$H_0 = U_{PMNS}\, H_3\, U_{PMNS}^+$$

Hamiltonian in matter

Add to energy in vacuum the potential which describes interaction of neutrino to matter

$H(n_e, E) = H_0 + V$ $\quad$ $V = \mathrm{diag}(V_e, 0, 0)$ $\quad$ in the flavor basis

Difference of potentials matters:

$V_e = \sqrt{2}\, G_F n_e$ $\quad$ due to the CC scattering on electrons

Can be derived by summation of Yukawa potentials with radius $1/m_W$ produced by electrons

$$V = 2\int_0^\infty dr\, r^2 \frac{g^2}{8r} e^{-m_W r}$$

after integration over angular variables

Eigenstates in matter

Eigenstates of the Hamiltonian in matter:

$$H(n_e, E) = H_0 + V(n_e)$$

Play the same role as mass states in vacuum

$$\nu_k \rightarrow \nu_{mk} \qquad k = 1, 2, 3$$

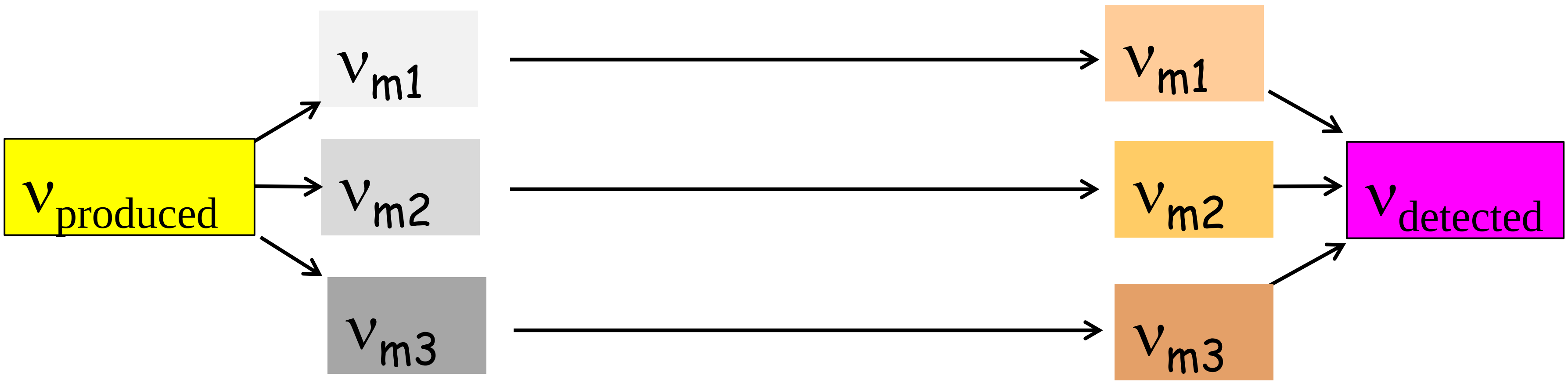
In matter with constant density they propagate independently.

Formally, they diagonalize Hamiltonian H. The Hamiltonian H in basis of ν_{mk} is diagonal. Consequently, equation of motions for them split.

Vacuum can be treated as matter with constant density and effect which depends on energy

Why notion of the eigenstates is important?

The best way to understand flavor evolution



Decompose initial state into eigenstates of propagation

By definition they propagate independently

Transitions between them negligible or small

Still properties (flavors) of the eigenstates may change

Projection onto detected state

Mixing in matter

Mixing in matter is determined with respect to eigenstates in matter

Mixing matrix in matter connects the flavor states with eigenstates in matter

$$\nu_f = U^m \nu_m$$

in the same way as in vacuum the PMNS matrix connects the flavor states with mass states:

$$U_{PMNS} \rightarrow U^m(n_e, E)$$

Formally U^m diagonalizes the Hamiltonian in matter

$$U^{m+} H U^m = H^{diag}$$

$$H^{diag} = diag(H_{1m}, H_{2m}, H_{3m})$$

eigenvalues of the Hamiltonian

Mixing in matter – dynamical variable

S.P. Mikheyev, A.Y.S. 1985

Since

$$H(n_e, E) = H_0(E) + V(n_e)$$

the mixing matrix in matter which diagonalizes $H(n_e, E)$

$$U^m = U^m(n_e, E)$$

depends on energy and density → becomes dynamical variable
in non-uniform medium
in contrast to vacuum mixing which is constant

Inverting relation:

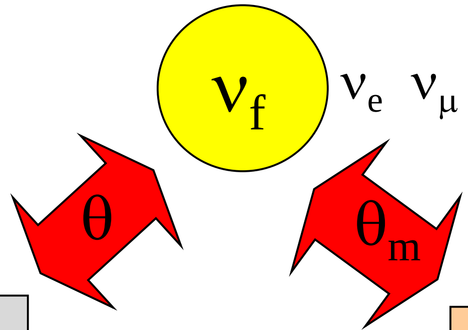
$$\nu_m = U^{m+}(n_e, E)\,\nu_f$$

which means that flavor composition of eigenstates depends on n_e and E

Mixing in matter

in vacuum:

H_0



ν_e ν_μ

in matter:

$H(n_e, E) = H_0 + V$

ν_1 ν_2 ν_{mass}

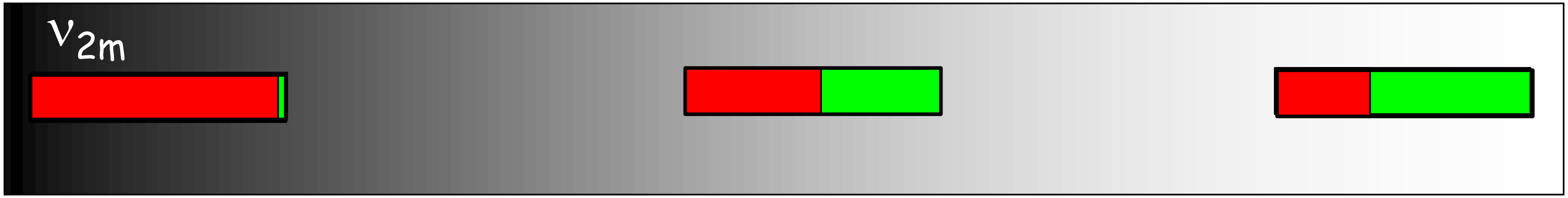
Eigenstates of H_0 in vacuum

ν_H ν_{1m} ν_{2m}

Eigenstates of H in medium

θ_m depends on n_e, E

Mixing angle determines flavor content of eigenstates of propagation



High density
mixing suppressed

Resonance: $l_\nu = l_0 \cos 2\theta$
- maximal mixing

Low density
Vacuum mixing

The MSW effects

- the flavor transformations driven by the energy and density dependence of the mixing in matter

$$\nu_f = U^m(E, n)\, \nu_H$$

Flavor states

Mixing matrix in matter

Eigenstates of Hamiltonian in mater - Eigenstates of propagation

Mixing angles $\theta^m(E, n)$ become dynamical variables

in contrast, to mixing in vacuum

Dependence of $\sin^2 2\theta^m$ on E and n has resonance character

Evolution equation for eigenstates. Adiabaticity

Varying density

Inserting in evolution equation for the flavor states $\nu_f = U^m \nu_m$

$$i \frac{d\nu_m}{dt} = \left(H^{diag} + i\, U^{m+} \frac{dU^m}{dt} \right) \nu_m$$

$H^{diag} = diag(H_{1m}, H_{2m}, H_{3m})$

off - diagonal

If density changes slowly enough, so that

$$\left(U^{m+} \frac{dU^m}{dt} \right)_{ij} \ll H_{im} - H_{jm}$$

adiabaticity condition

equation for the eigenstates splits:

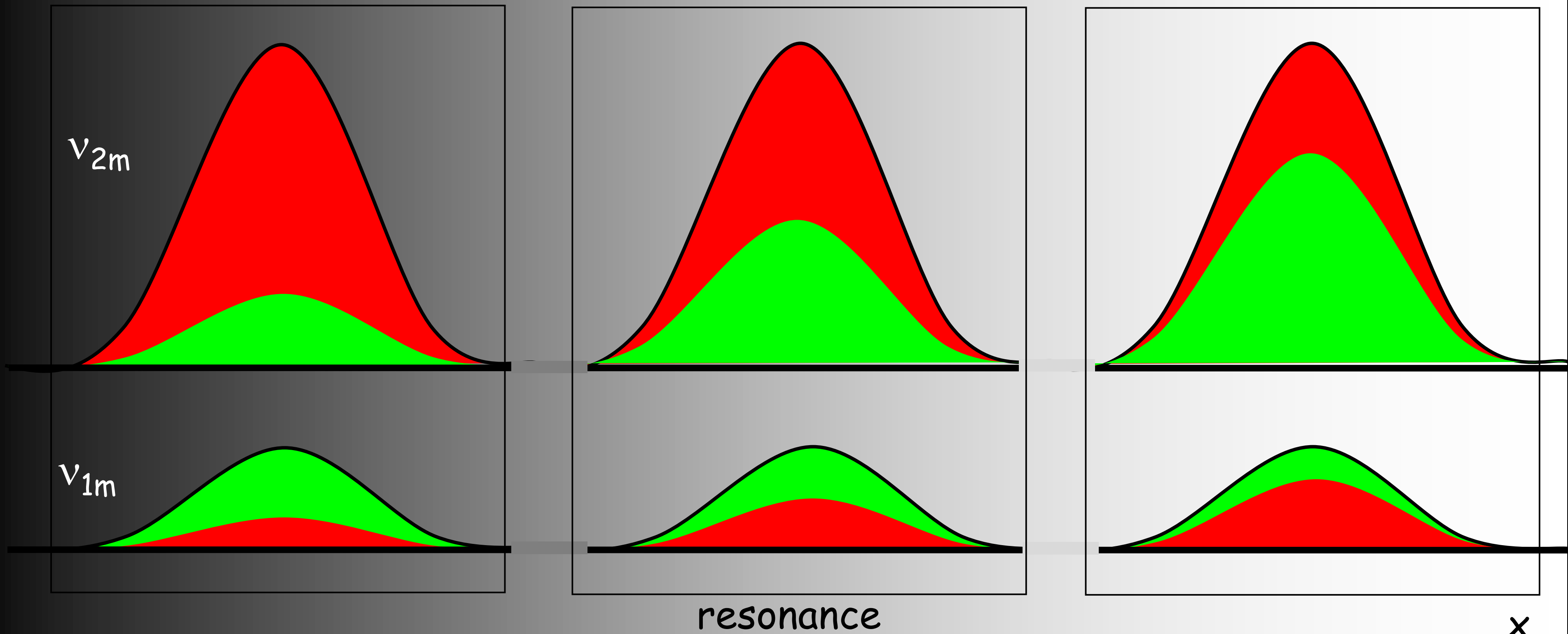
$$i \frac{d\nu_m}{dt} = H^{diag} \nu_m$$

The eigenstates evolve independently, transitions $\nu_{im} \Leftrightarrow \nu_{jm}$ are absent as in constant density

In contrast to constant density case the flavors of ν_{im} change according to density change

Adiabatic conversion

in general if density changes slowly (adiabatically)

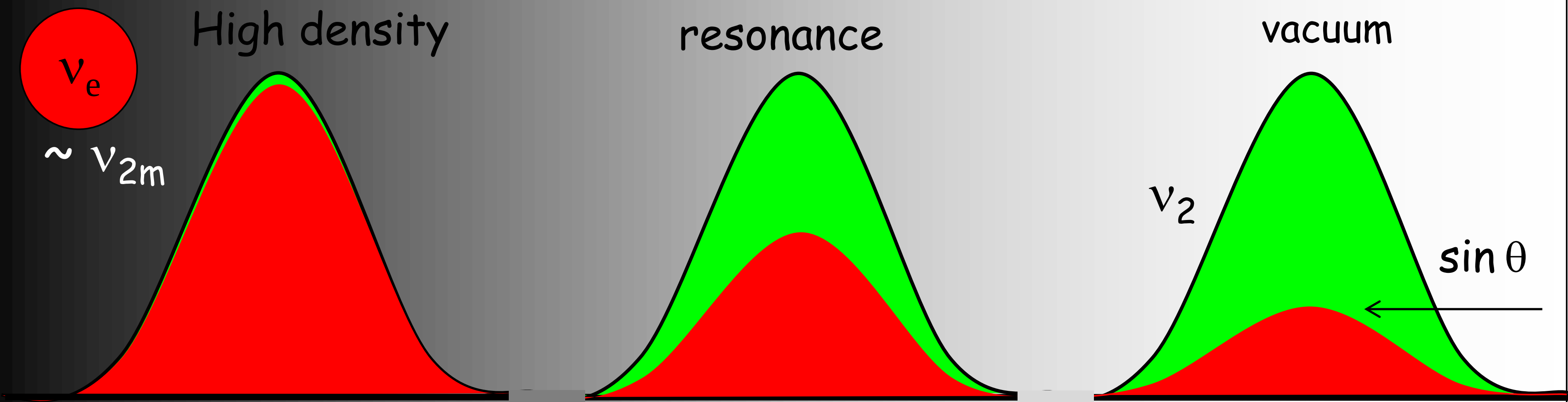


if initial density is not very big:
mixing is not suppressed
→ both eigenstates are produced → interference
→ oscillations

- the amplitudes of the wave packets do not change
- flavors of the eigenstates being determined by mixing angle follow the density change

Varying density

Non-oscillatory transition



$\langle \nu_e | \nu_2 \rangle = \sin\theta$ x

mixing is very small

Single eigenstate:
→ no interference
→ no oscillations
→ phase is irrelevant

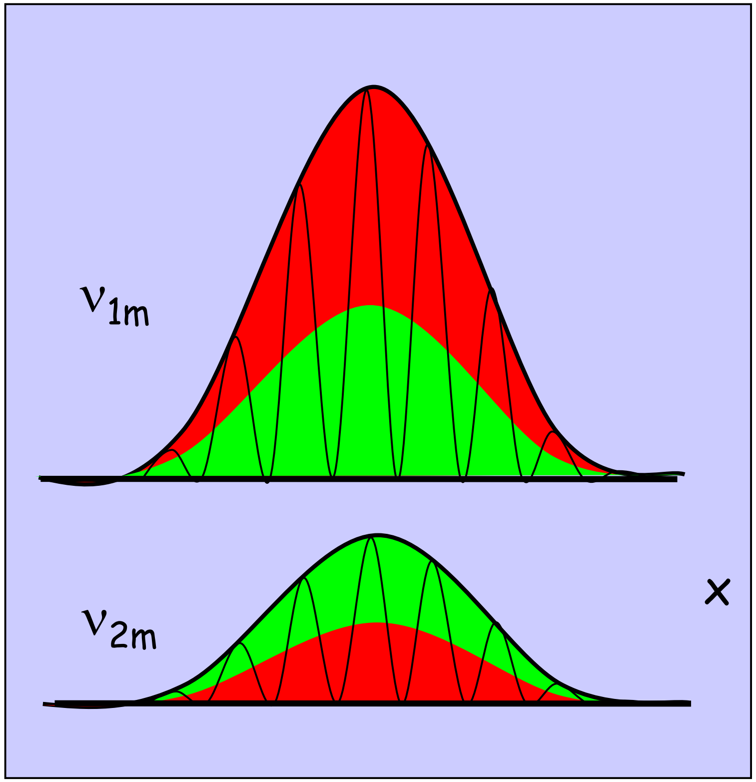
Survival probability $\boxed{P_{ee} = \sin^2\theta}$

if density changes slowly (adiabatically)
→ no other eigenstate appear

$$\nu_{2m} \rightarrow \nu_2$$

Mixing and therefore the flavor content changes according to density change

Oscillations: phase effect



Vacuum, constant density medium:

Resonance - maximal mixing in matter – oscillations with maximal depth

$\theta_m = \pi/4$

Resonance condition:

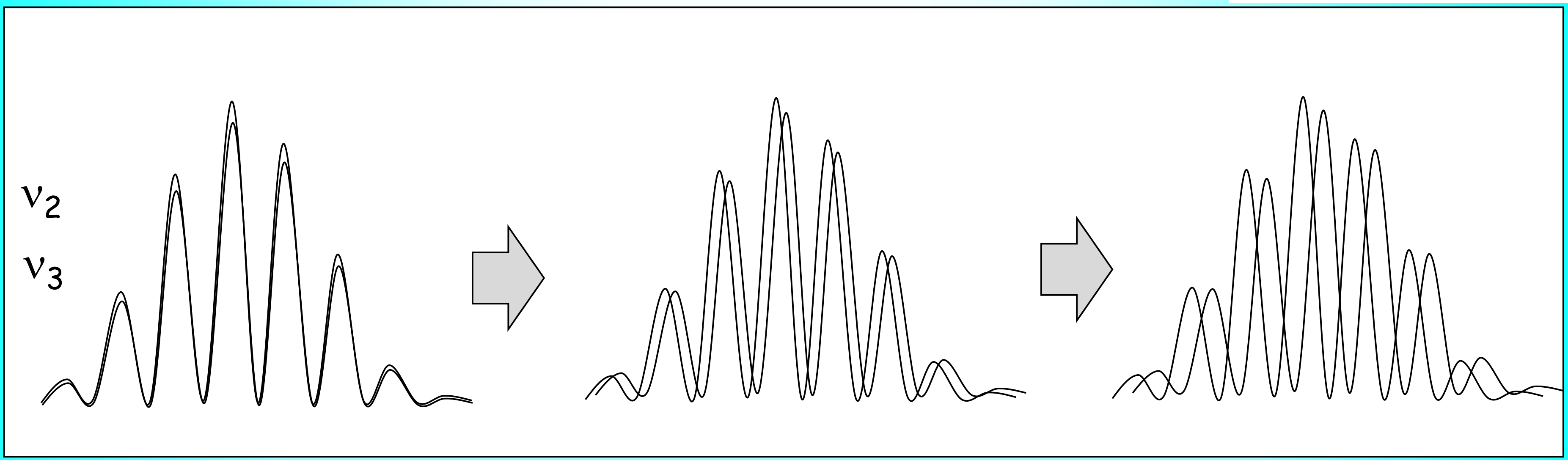
$$V = \cos 2\theta \frac{\Delta m^2}{2E}$$

Oscillations

Difference of masses of ν_2 and ν_3 → Difference of phase velocities → Phase difference increase with distance

$$\phi = \frac{\Delta m^2 L}{2E}$$

$$\Delta m^2 = m_3^2 - m_2^2$$



distance

L

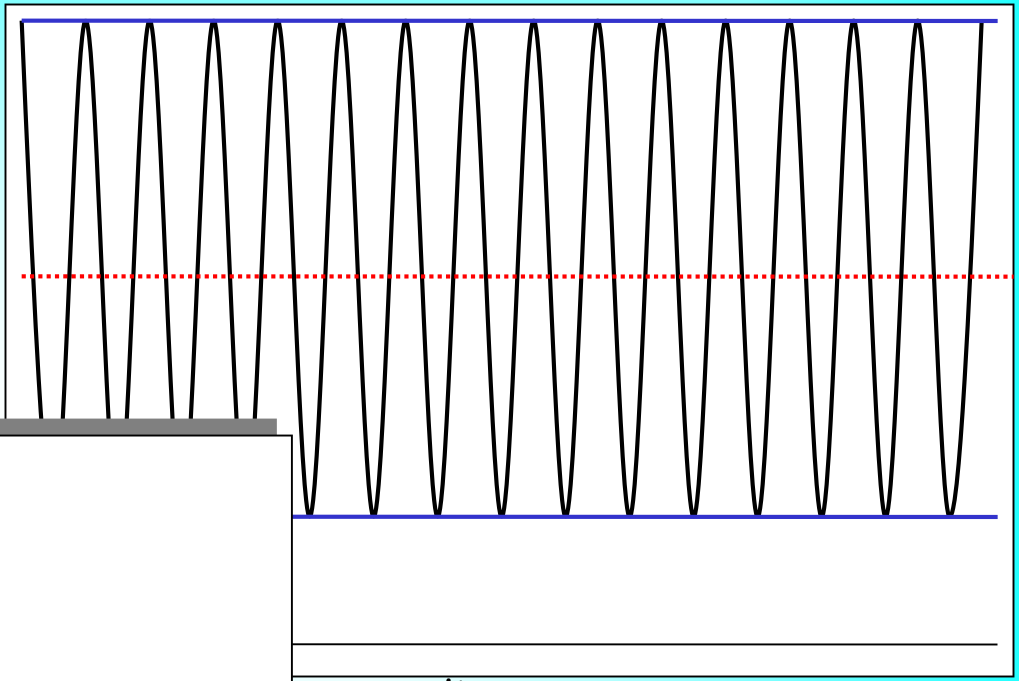
$\phi = 0$

shift of oscillatory patterns

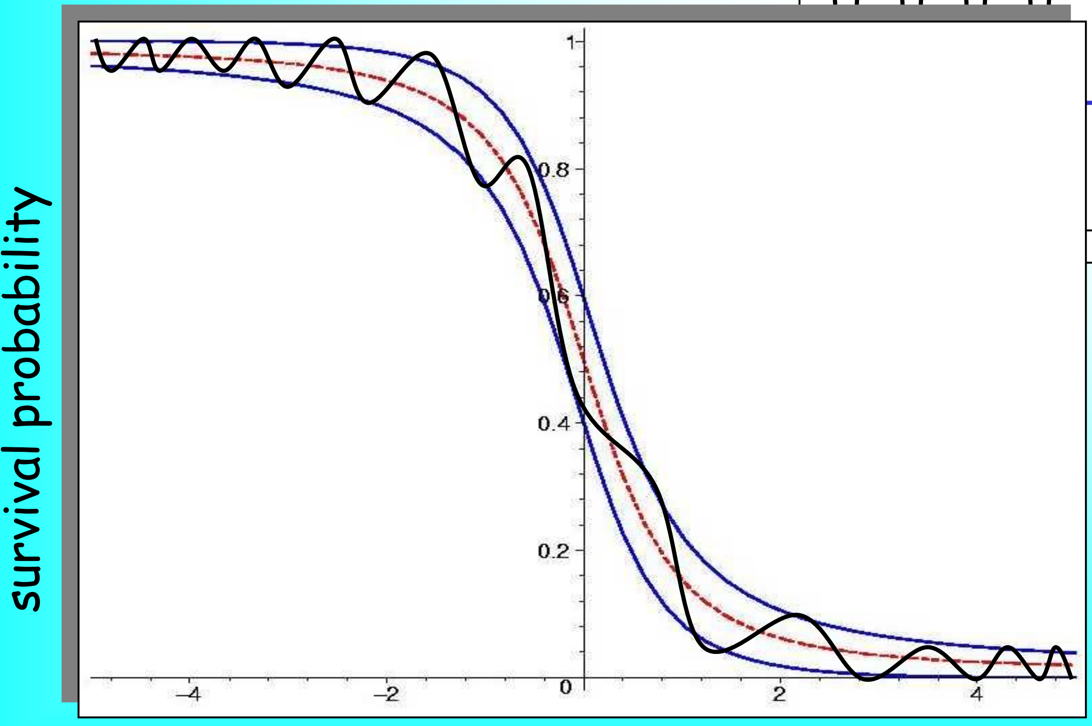
ν_μ

Spatial picture

Oscillations

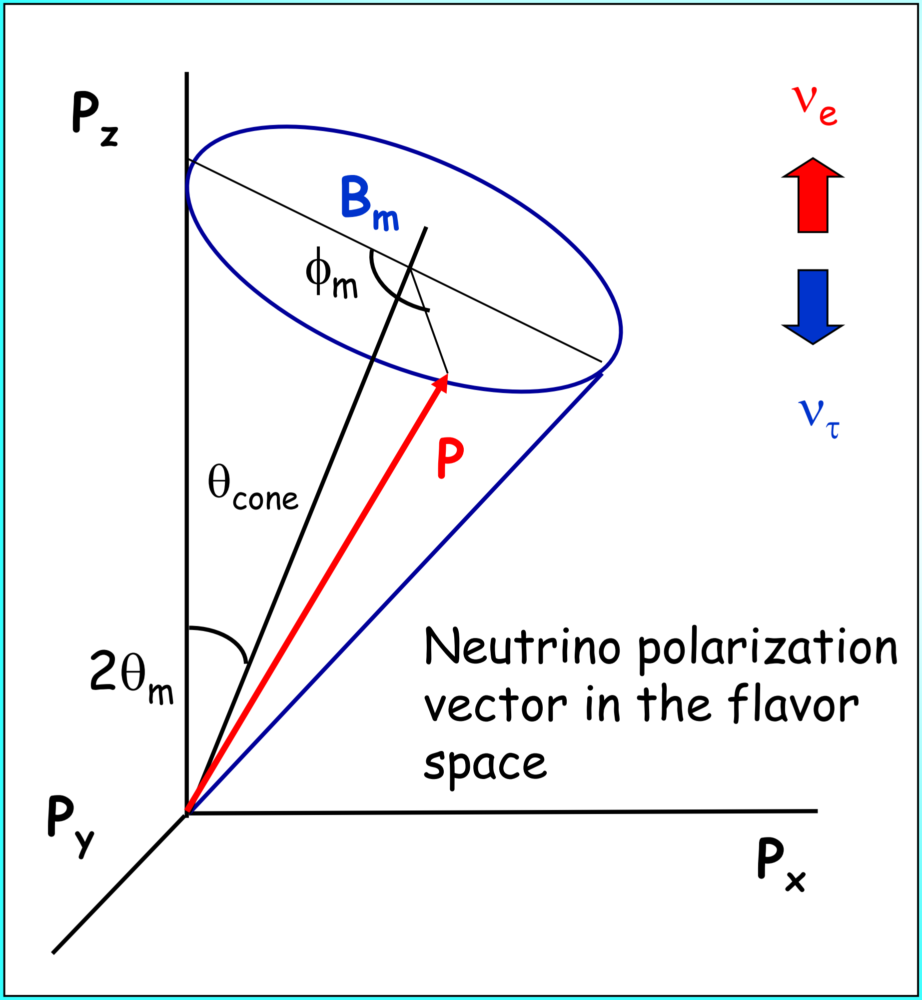


Adiabatic conversion



Useful analogy

of oscillations with the electron spin precession in the magnetic field



$| \mathbf{P} | = \frac{1}{2}$ polarization vector

$$\mathbf{B_m} = \frac{2\pi}{l_m} (\sin 2\theta_m, \ 0, \ \cos 2\theta_m)$$

$$P_{ee} = \nu_e^+ \nu_e = P_Z + 1/2$$

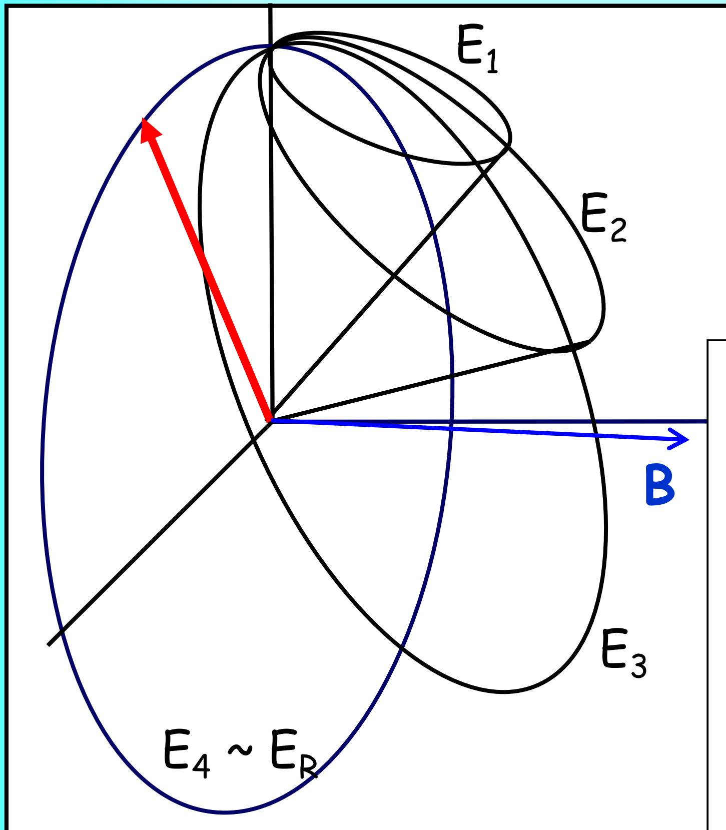
$\phi_m = 2\pi t / l_m$ oscillation phase

Degrees of freedom:

θ_m (n, E) - mixing angle
ϕ_m (n, E) - phase
θ_{cone} (dn/dx) - cone angle

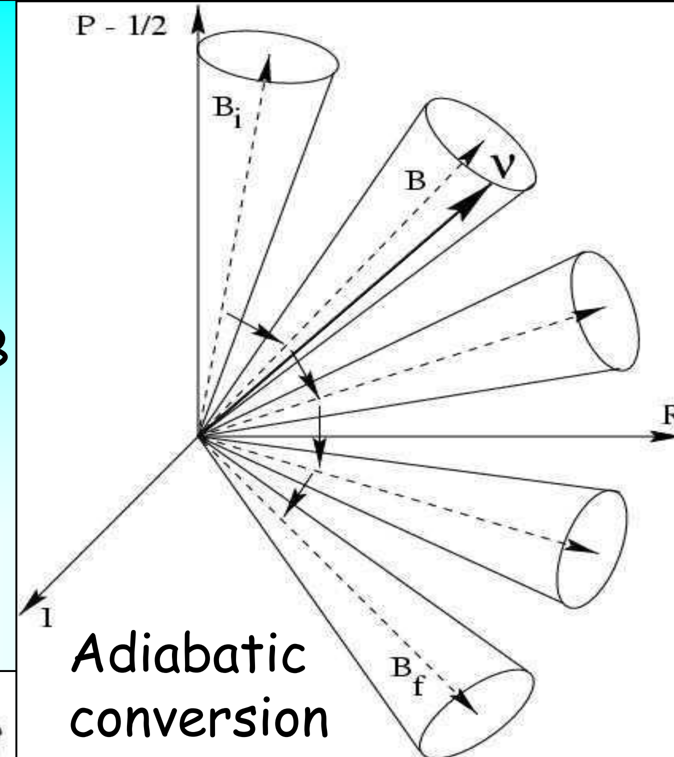
Graphic representation

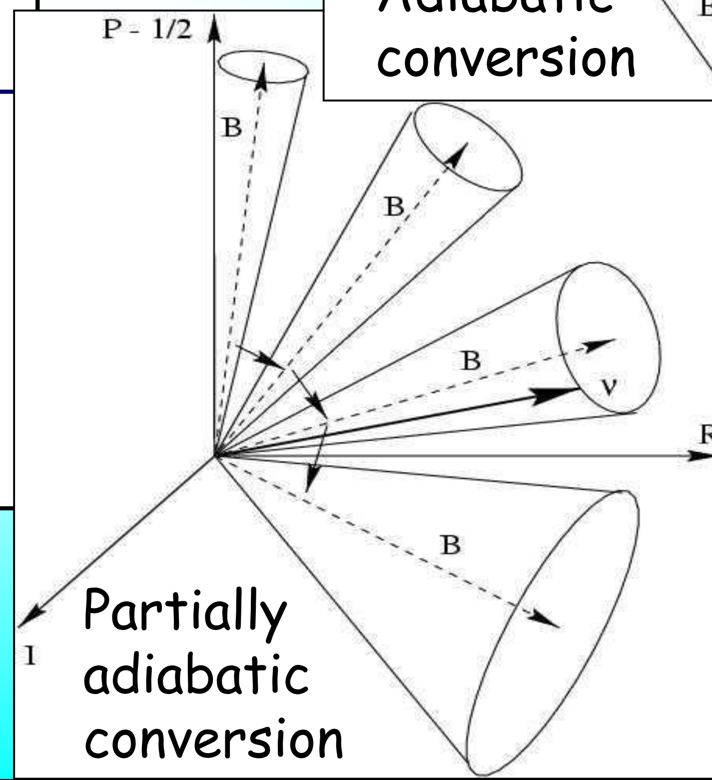
Slowly moving B



Resonance enhancement of oscillations

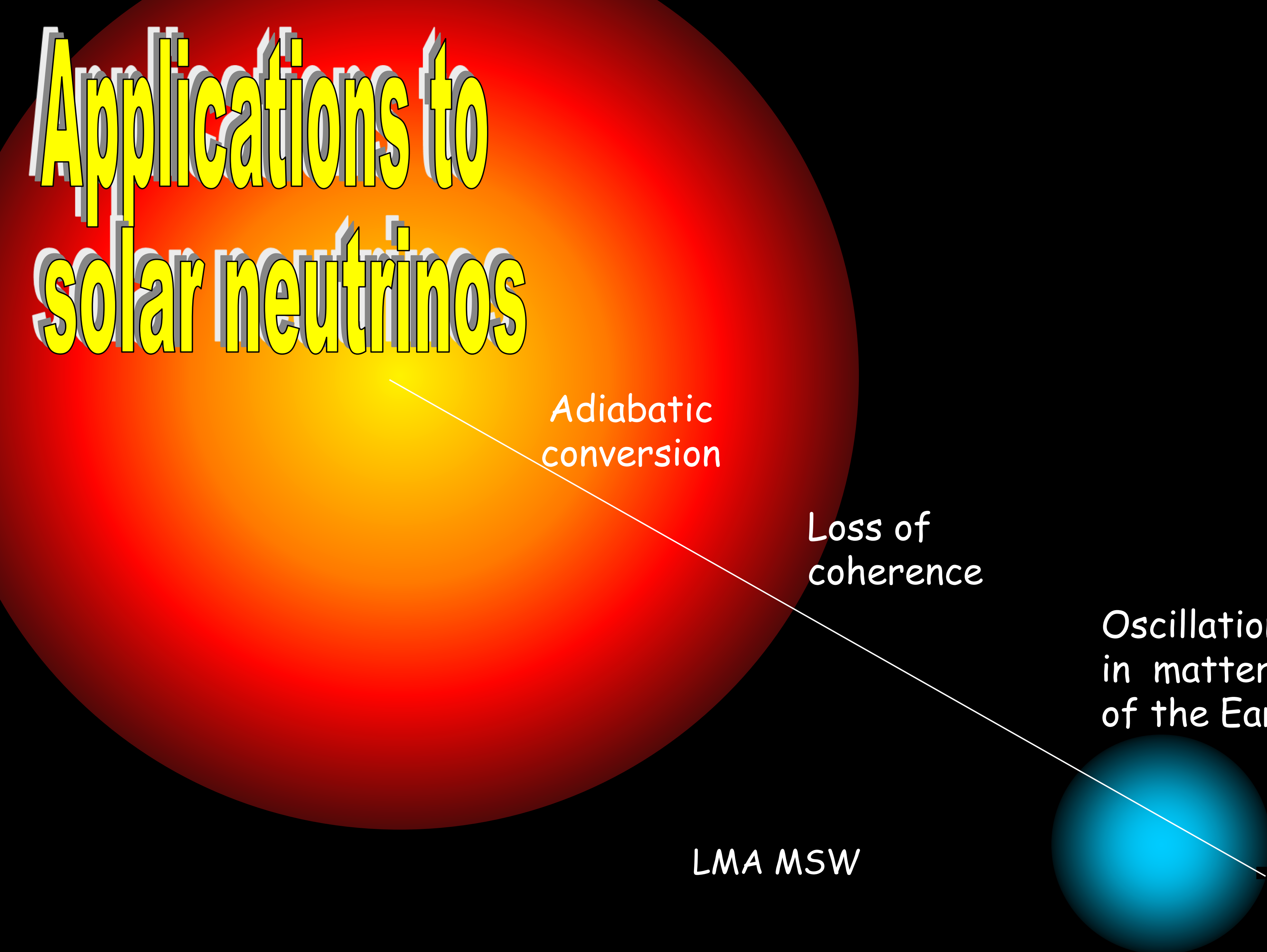
$E_1 < E_2 < E_3 < E_4$



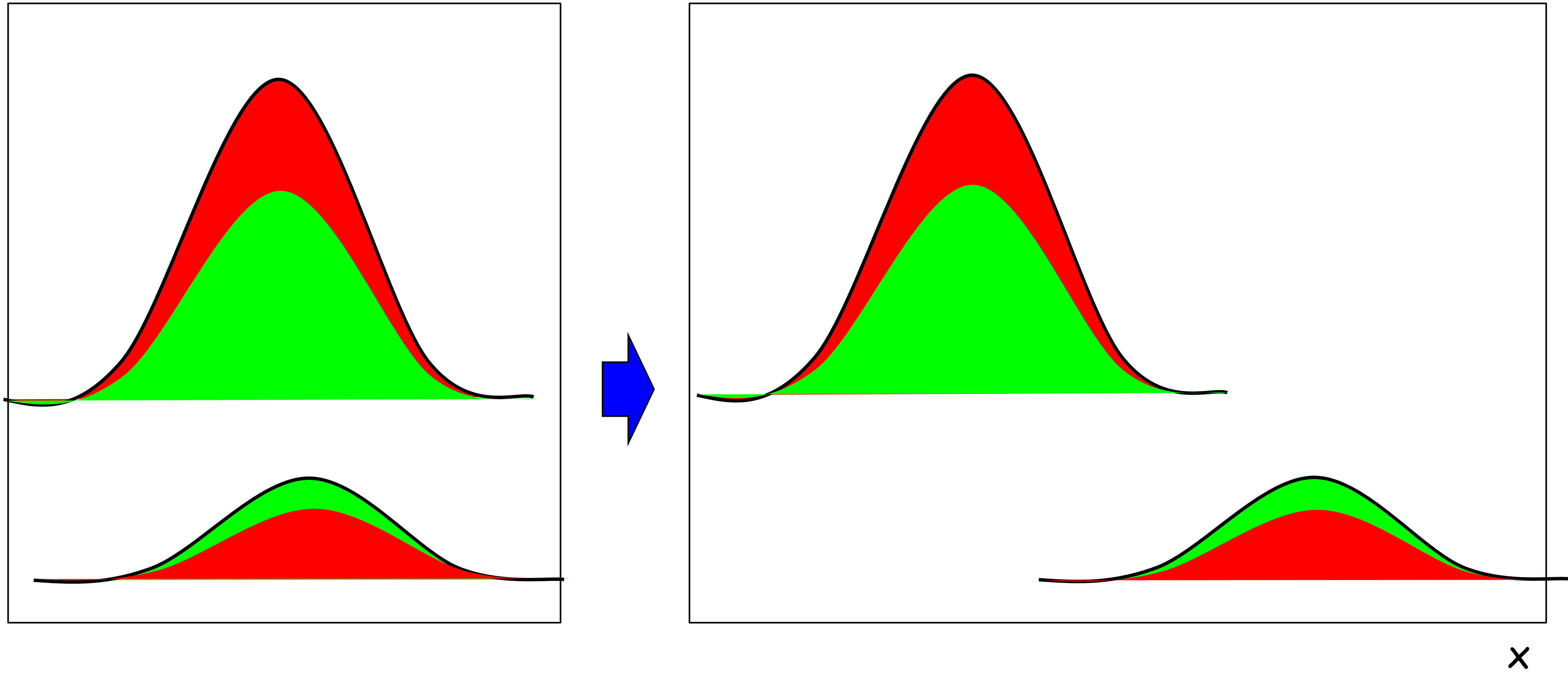


Fastly moving B

Applications to solar neutrinos

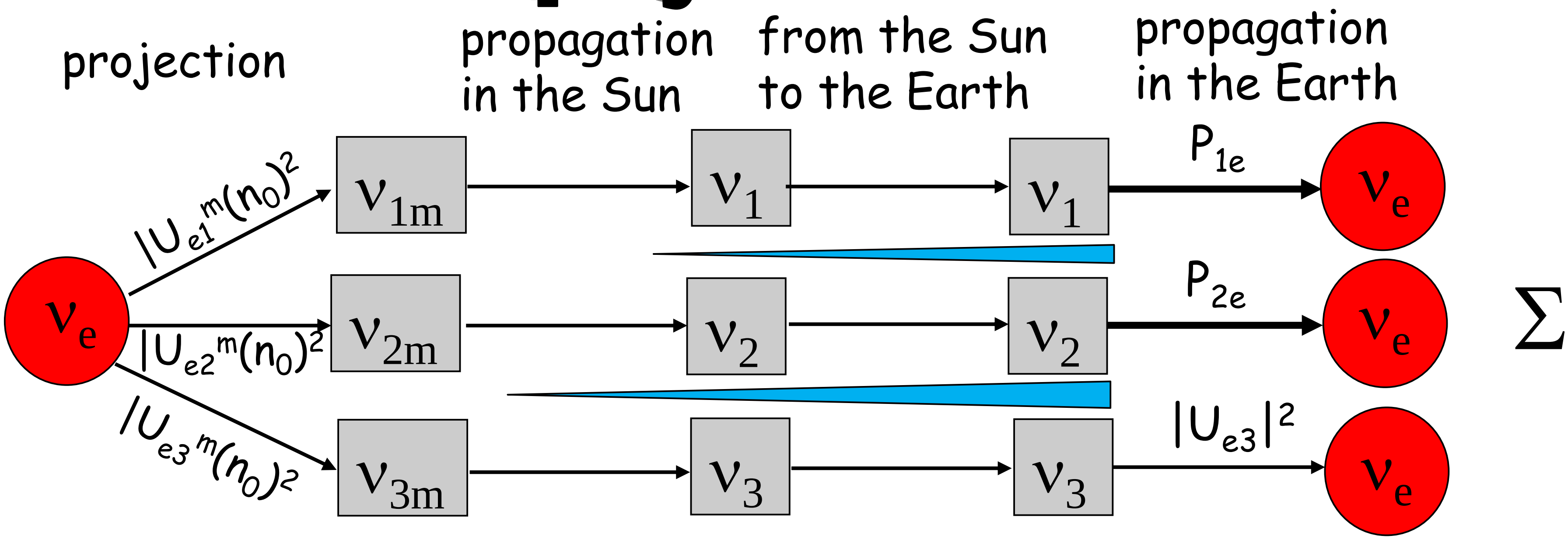


Loss of coherence



From the Sun to the Earth

LMA-MSW physics



mixing at production

adiabatic conversion

loss of coherence

oscillations in multi-layer medium

$$P_{ee} = \Sigma_i |U_{ei}^m(n_0)|^2 \, P_{ie}$$

during a day

$$P_{ie} = |U_{ei}|^2$$

In the Sun: scale invariance: no dependence of P_{ee} on distance and phase - oscillations irrelevant

In terms of mixing angles

Using the same standard parametrization for mixing matrix in matter:

$U_{e1}^m = c_{13}^m \cos\theta_{12}^m$, $U_{e2}^m = c_{13}^m \sin\theta_{12}^m$, $|U_{e3}^m| = s_{13}^m$

($c_{13} = \cos\theta_{13}$, $c_{13}^m = \cos\theta_{13}^m$, etc.)

and regeneration factor one finds from general formula

$$P_{ee} = c_{13}^2 c_{13}^{m2} P_2^{ad} + s_{13}^2 s_{13}^{m2} - c_{13}^{m2} \cos 2\theta_{12}^m f_{reg}$$

where $$P_2^{ad} = \sin^2\theta_{12} + \cos 2\theta_{12} \cos\theta_{12}^m$$

or $$P_2^{ad} = \tfrac{1}{2} (1 + \cos 2\theta_{12} \cos 2\theta_{12}^m)$$

Here the mixing parameters in matter $\theta_{ij}^m = \theta_{ij}^m(n_0, E)$ should be computed in the neutrino production point

For high energy part

Complete expression (1-2 mixing)

$$P = \sin^2\theta + \cos 2\theta \cos^2\theta_m^0 + F_{reg}$$

non-oscillatory transition

contribution from oscillations in the Sun

Contribution from oscillations in the Earth

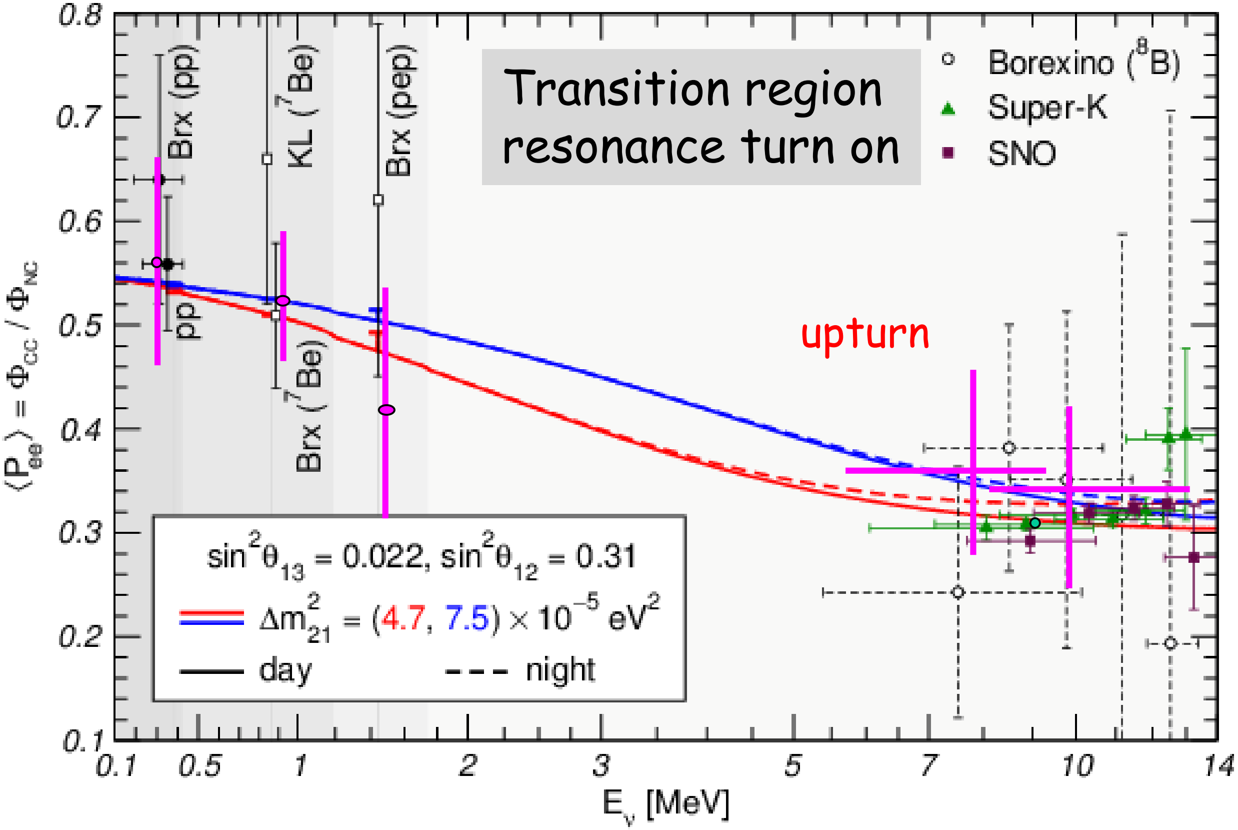
θ_m^0 - mixing angle in matter in production point

P(E) is determined by the energy dependence of the mixing angle in production point

Spectroscopy

M. Maltoni, A.Y.S. 1507.05287 [hep-ph]

Borexino Collaboration (Agostini, M. et al.) arXiv:1707.09279 [hep-ex]



LMA MSW prediction for two different values of Δm_{21}^2

best fit value from solar data

best global fit

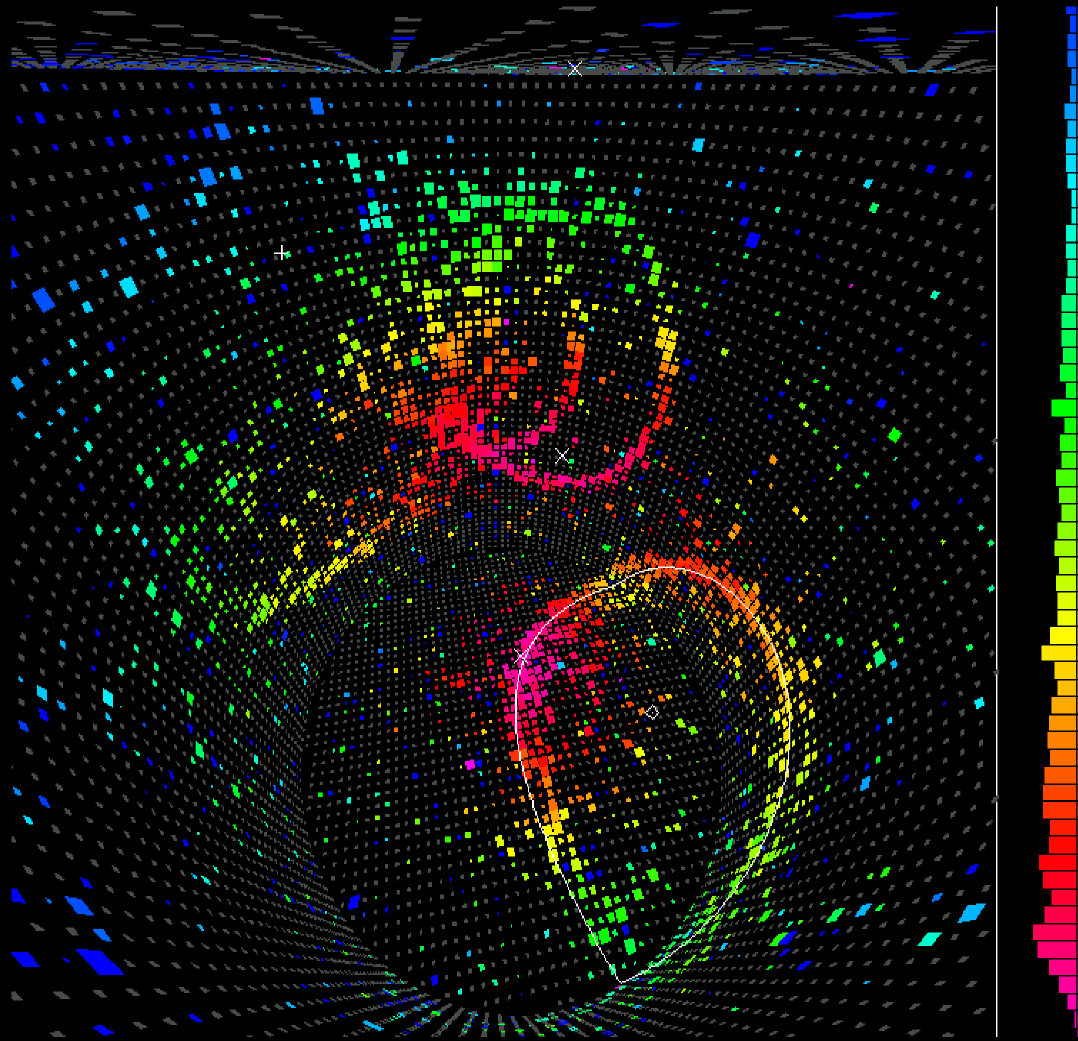
Reconstructed exp. points for SK, SNO and BOREXINO at high energies

BOREXINO:

pep: (phase I + phase II – ideal agreement)

B: 2 times smaller errors, upturn...

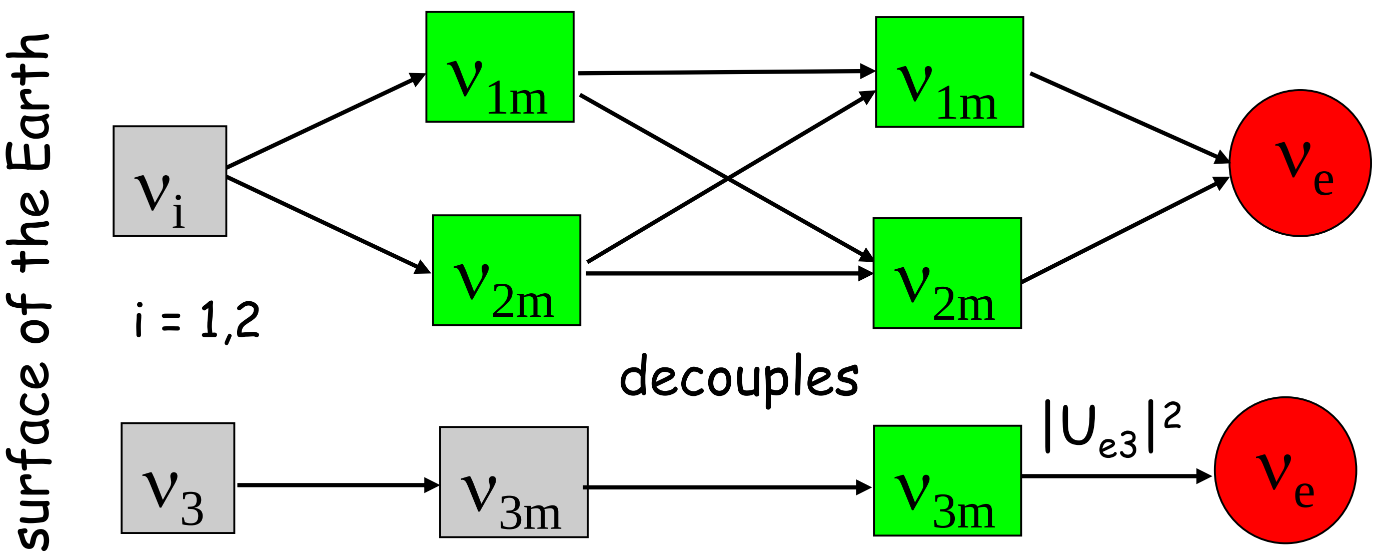
Oscillations
In the Earth



Oscillations in the Earth

Distance and phase matter

propagation in the Earth projection



P_{ie}

$P_{3e} = |U_{e3}|^2$

Σ

mixing of mass states in matter

oscillations in multi-layer medium

flavor mixing in matter

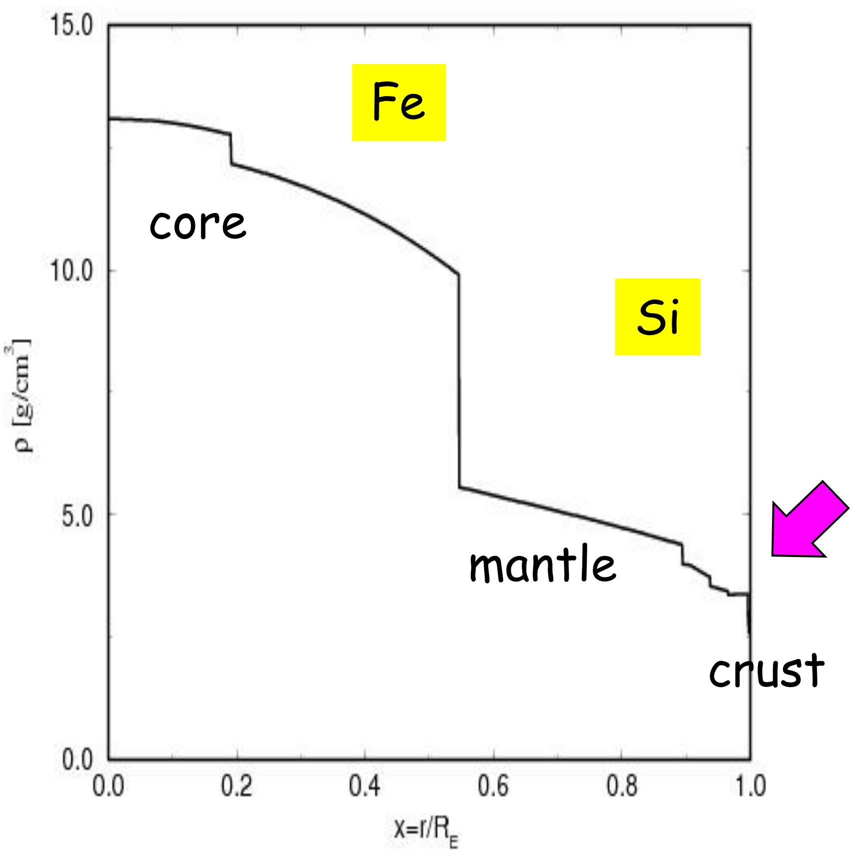
$P_i = |U_{ei}^m(n_0)|^2$

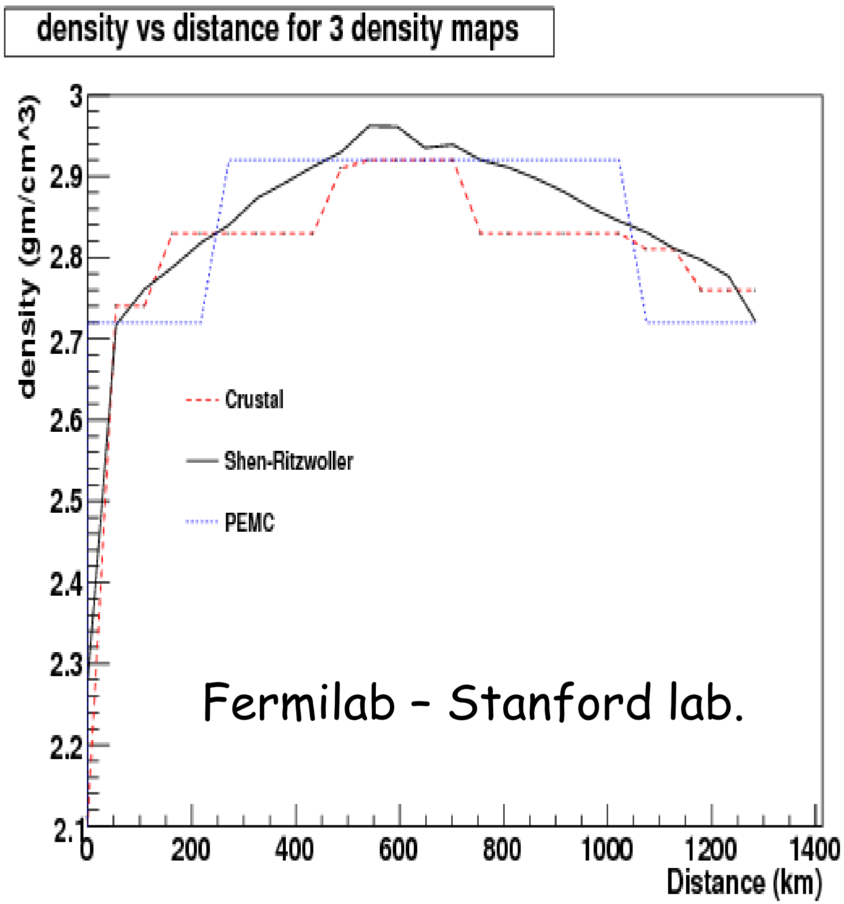
mixing at production in the Sun

Adiabaticity violation at the border between layers

The earth density profile

PREM model





A.M. Dziewonski
D.L Anderson 1981

$R_e = 6371$ km

Byron Roe, Phys.Rev. D95 (2017) no.11, 113004 arXiv:1707.02322 [hep-ex]

Oscillations in the Earth

Incoherent fluxes of mass state arrive at the Earth.
They split into eigenstates in matter and oscillate.

Mixing of the mass states in matter

$$U^{mass} = U_{PMNS}^{+} U^{m}$$

For 2ν case

$$\sin 2\theta' = \frac{c_{13}^2 \varepsilon \sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} - c_{13}^2 \varepsilon)^2 + \sin^2 2\theta_{12}}} = c_{13}^2 \varepsilon \sin 2\theta_{12}^m$$

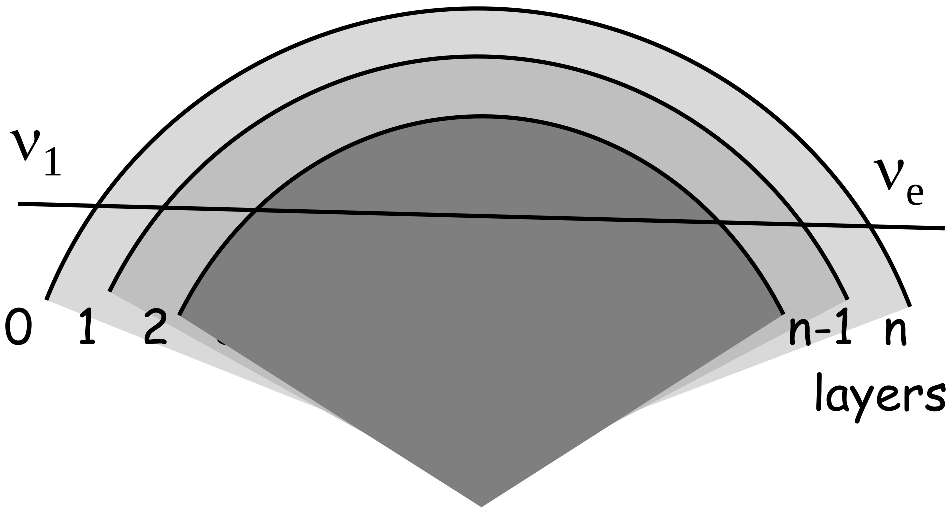
$$\varepsilon = \frac{2VE}{\Delta m_{21}^2} = 0.03\, E_{10}\, \rho_{2.6}$$

determines smallness of effects
Low density regime

MeV g/cm^3

Regeneration

A. Ioannisian, A. Smirnov, D. Wyler, Phys.Rev. D96 (2017) no.3, 036005 arXiv:1702.06097 [hep-ph]



Layers with slowly changing density and density jump

Evolution matrix (matrix of transition amplitudes)

$$S = U^m{}_n \, \Pi_k \, D_k U_{k,k-1}$$

flavor mixing matrix, at the detector

D_k - describe the adiabatic evolution within layers:

$$D_k = \mathrm{diag}\,(e^{-0.5i\phi_\kappa},\ e^{0.5i\phi_\kappa})$$

$$\phi_\kappa = \int dx(H_{2m} - H_{1m})$$

adiabatic phase acquired in k layer

$U_{k,k-1}$ - describes change of basis of eigenstates between k and k-1 layers

$$U_{k,k-1} = U(-\Delta\theta_{k-1})$$

$\Delta\theta_{k-1}$ -change of the mixing angle in matter after k-1 layer

Oscillation waves

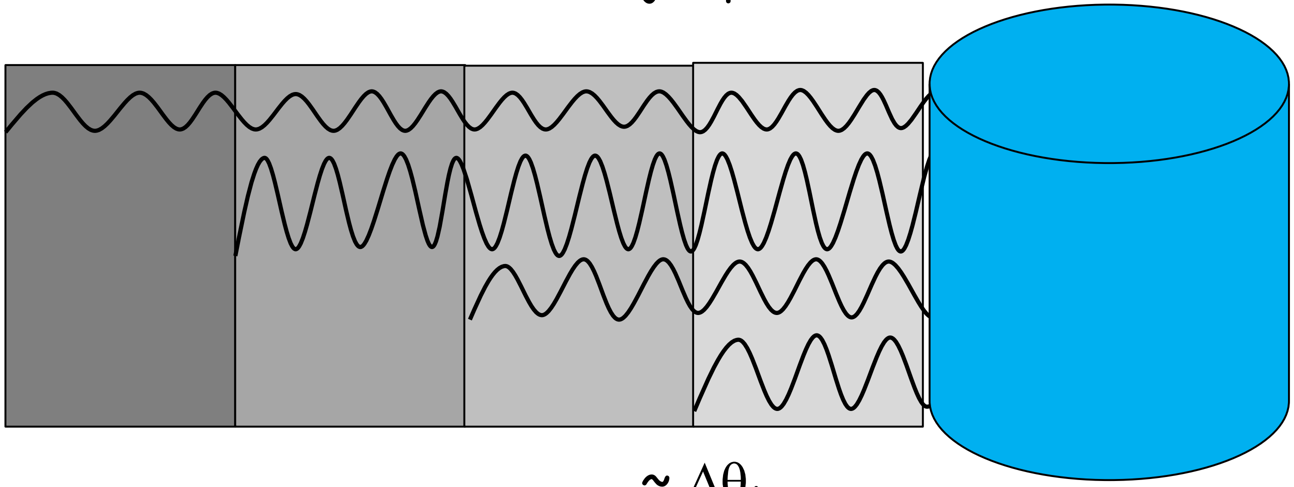
The lowest order plus waves emitted from different jumps

$$P_{1e} \sim c_{13}^2 \cos^2\theta_n^f + c_{13}^2 \sin 2\theta_n^f \, \Sigma_{j = 0 \ldots n-1} \sin\Delta\theta_j \cos \phi_j^{after}$$

initial wave without density jumps

sum over density jumps

total phase acquired after jump j



~ $\Delta\theta_j$

superposition of waves

the amplitude of wave: $c_{13}^2 \sin 2\theta_n^f \sin\Delta\theta_j$

$$\sin \Delta\theta_j = c_{13}^2 \sin 2\theta_{12} \, \Delta V_j \, \frac{E}{\Delta m_{21}^2}$$

Integral formula

A. Ioannisian and A. Y. S., PRL 93, 241801 (2004), hep-ph/0404060

Regeneration factor

$$f_{reg} = P_{1e} - P_{1e}^{0} = P_{1e} - c_{13}^{2}\cos^{2}\theta_{12}$$

determines the day-night asymmetry

In the integral form:

$$f_{reg} = -\tfrac{1}{2}\, c_{13}^{4}\sin^{2}2\theta_{12} \int_{x_0}^{x_f} dx\, V(x) \sin \phi^{m}(x \rightarrow x_f)$$

the phase acquired from the point x to the final point of trajectory

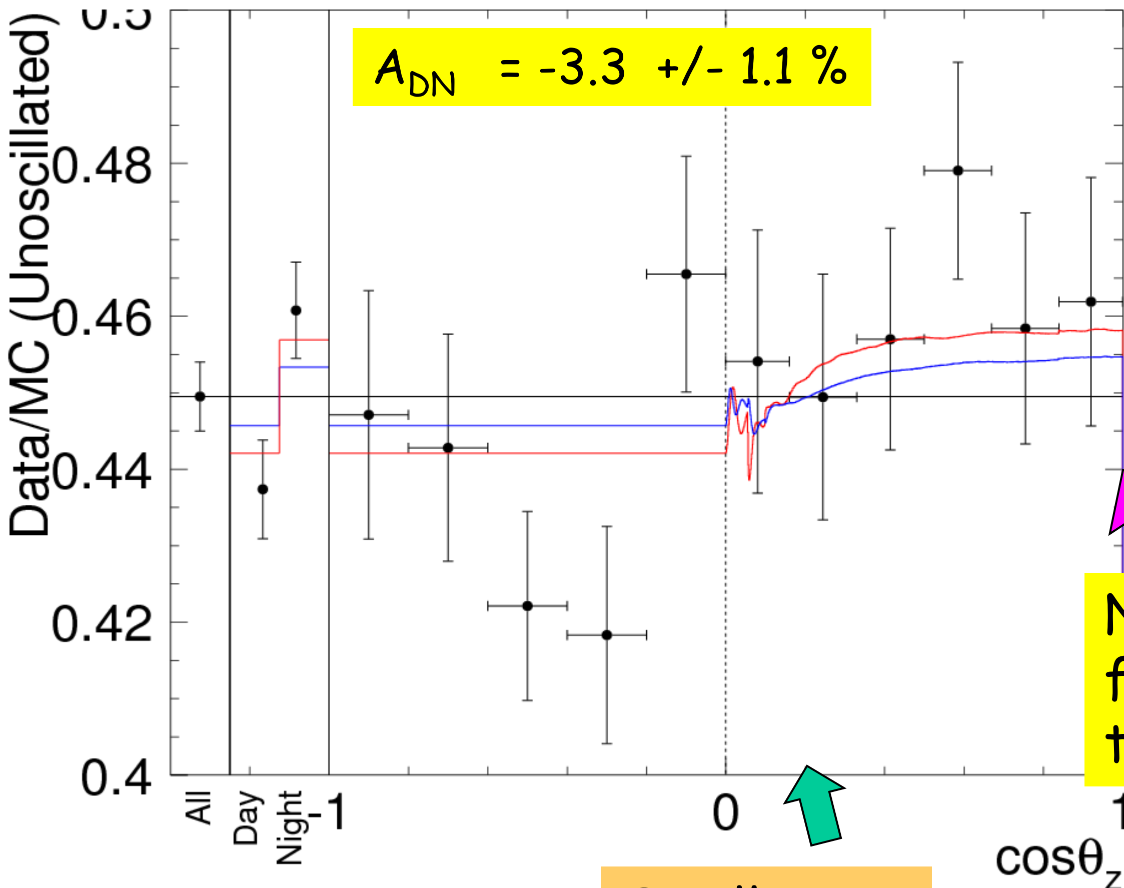
$$\phi^{m}(x \rightarrow x_f)\,(E) = \int_{x}^{x_f} dx\, \Delta_{12}^{m}(x)$$

For potential with jumps explicit integration in f_{reg} reproduces the result of sum of waves emitted from the jumps

SK: Earth matter effect

SK Collaboration (Abe, K. et al.) arXiv:1606.07538 [hep-ex]

SK-IV solar zenith angle dependence



Strong fluctuations

No enhancement for core crossing trajectories

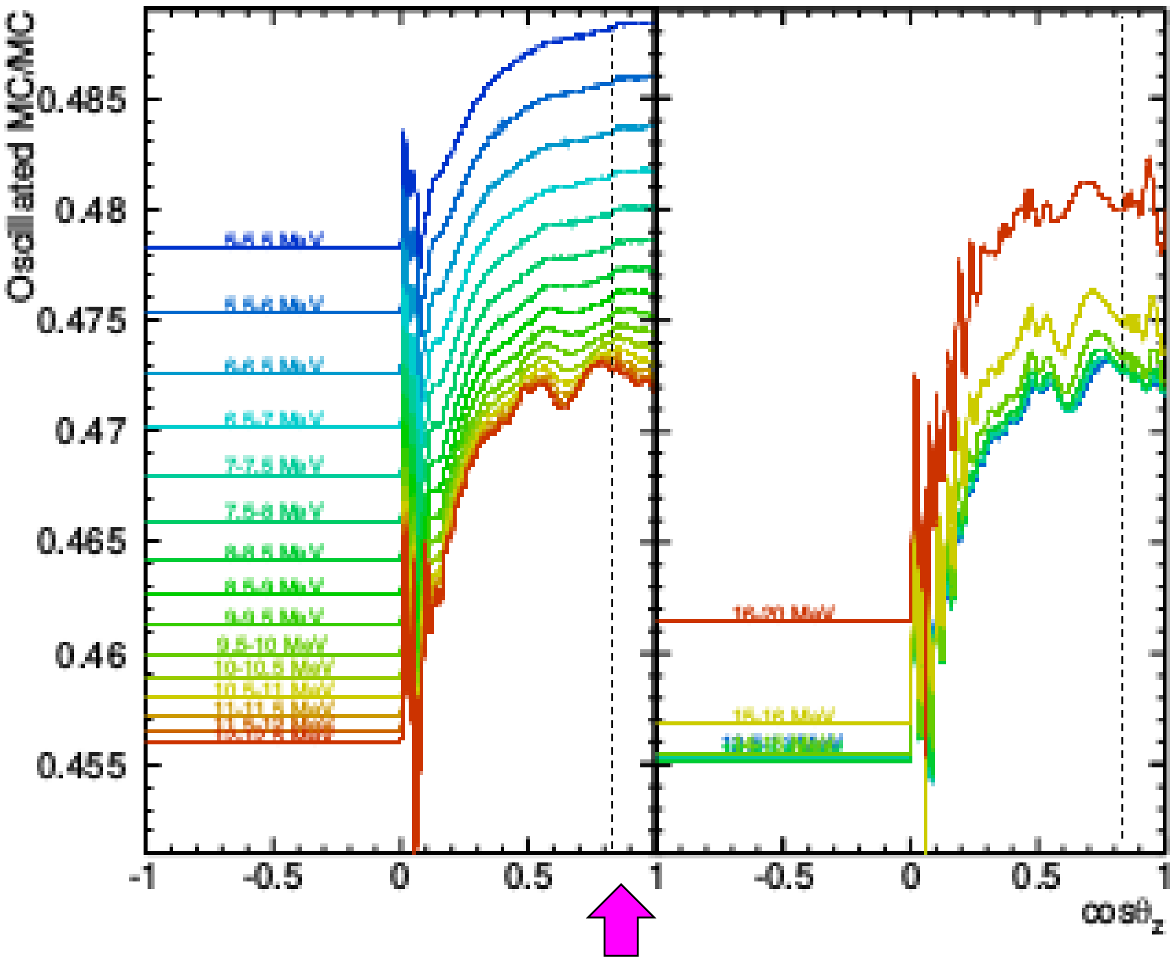
Explained by Attenuation effect

Generic features:

Oscillatory pattern

dip

Attenuation effect



Core crossing trajectories

M. Smy

Predicted solar zenith angle variations of SK the signal
$\Delta m^2 = 6.3 \times 10^{-5}$ eV ^{2},
$\tan 2\theta = 0.52$

No enhancement of the effect for core-crossing trajectories

Attenuation effect

A. Ioannisian, A. Y. Smirnov, Phys.Rev.Lett., 93, 241801 (2004), 0404060 [hep-ph]

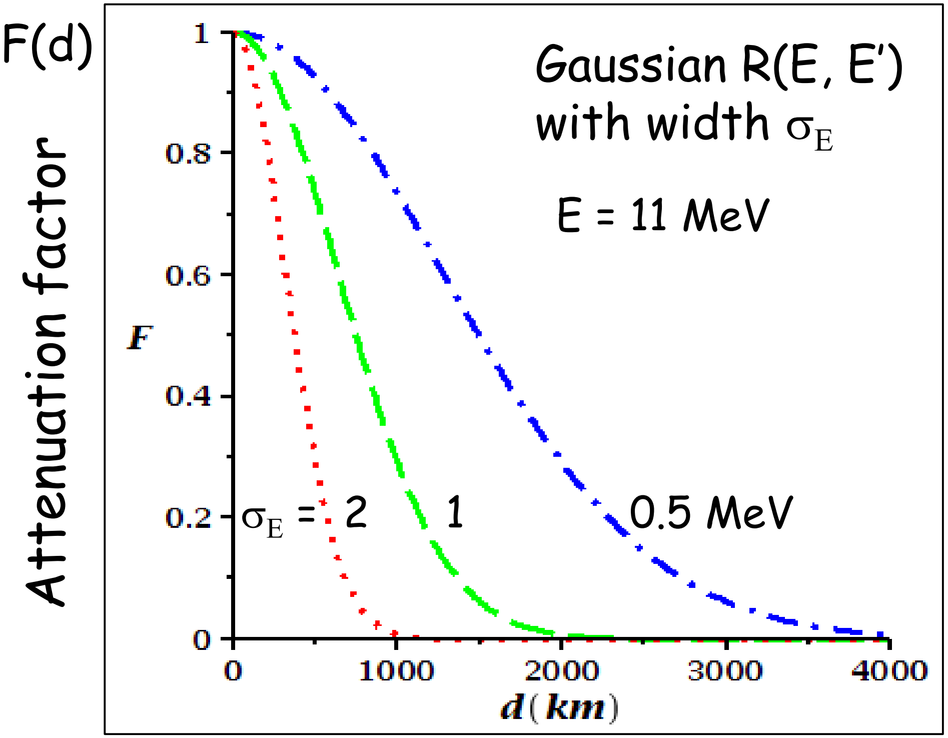
Integration with the energy resolution function R(E, E′):

$$\langle f_{reg} \rangle = \int dE' \, R(E, E') \, f_{reg}(E')$$

$$\langle f_{reg} \rangle = 0.5 \sin^2 2\theta \int_{x_0}^{x_f} dx \, F(x_f - x) \, V(x) \, \sin\Phi^m(x \rightarrow x_f)$$

Permuting E′ and x integrations

F(d)



The sensitivity to remote structures d > λ_{att} is suppressed

Attenuation length

$$\lambda_{att} = l_\nu \frac{E}{\pi \sigma_E}$$

l_ν is the oscillation length

The better the energy resolution, the deeper structures can be seen

Attenuation and decoherence

The oscillation phase acquired along the attenuation length:

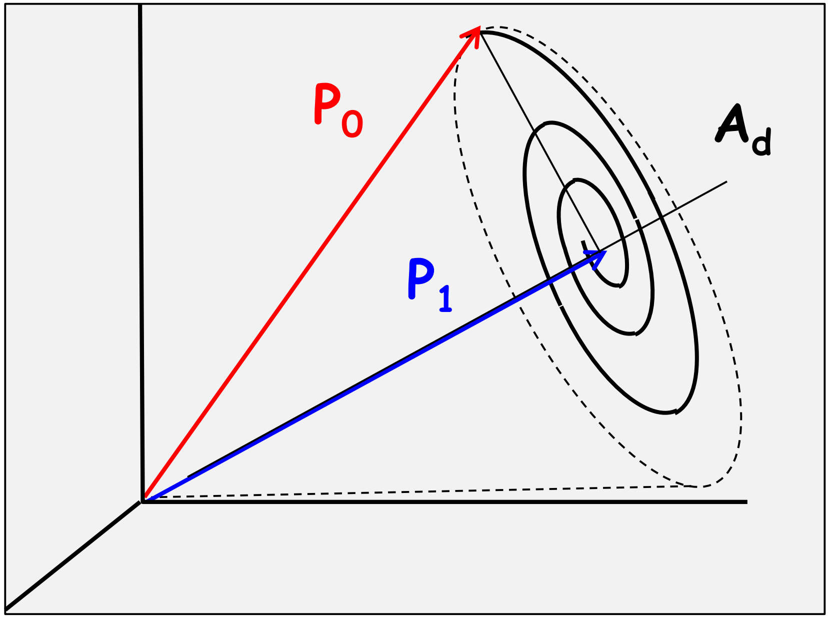
$$\phi = 2\pi \frac{\lambda_{att}}{l_\nu} = 2\pi \frac{E}{\pi\sigma_E}$$

Difference of phases with ΔE

$$\Delta\phi = 2\pi \frac{\Delta E}{\pi\sigma_E}$$

For $\Delta E = \pi\sigma_E$ $\quad \Delta\phi = 2\pi$

- integration over the energy resolution interval leads to averaging of oscillations
- λ_{att} is the distance over which oscillations observed with the energy resolution σ_E are averaged



Averaging – loss of coherence

$P_0 \rightarrow P_1$

converges to its projection onto axis of eigenstates A_d

A.N. Ioannisian, A. Yu. S. Phys.Rev. D96 (2017) no.8, 083009, 1705.04252 [hep-ph]

Paradoxes of attenuation

A.N. Ioannisian, A. Yu. Smirnov
Phys.Rev. D96 (2017) no.8, 083009
arXiv:1705.04252 [hep-ph]

Not only decoherence: effect does not disappear completely.
Even for very large distances: it survives in the ε^2 level

Info. about structure is still stored in spite of averaging

$\nu_1 \rightarrow \nu_e$ - channel

Remote structures are attenuated to the ε^2 level;
near structures are seen at ε

$\nu_e \rightarrow \nu_1$ - channel

Near structures are attenuated the ε^2 level;
remote structures are seen at ε

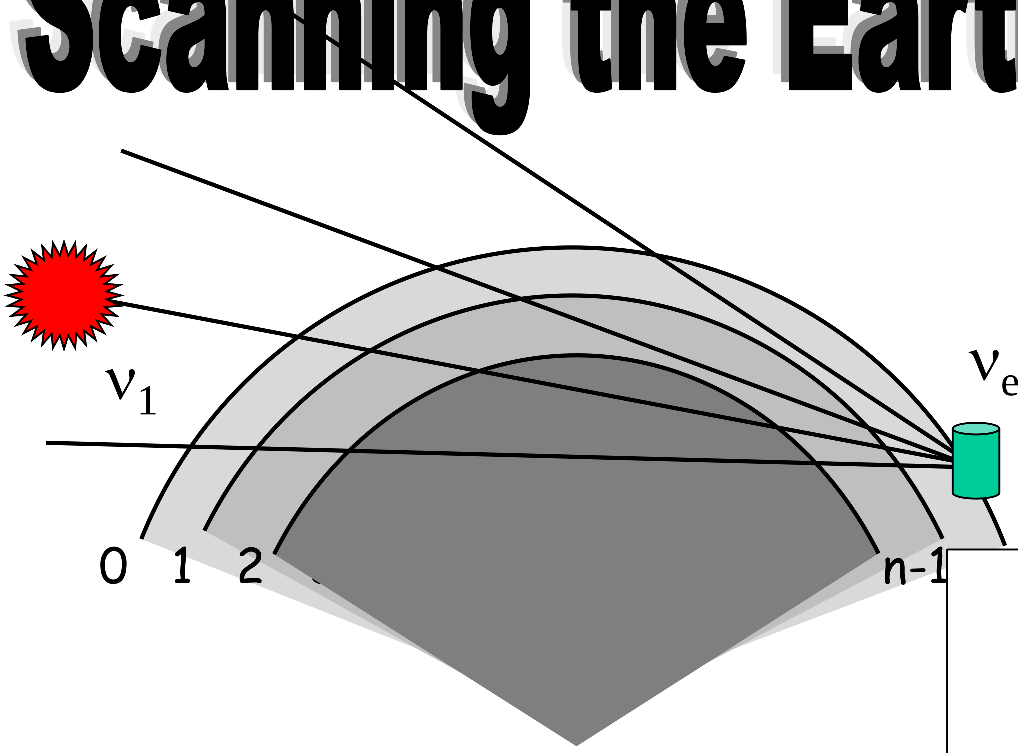
T-symmetry

$\nu_e \rightarrow \nu_e$ - channel

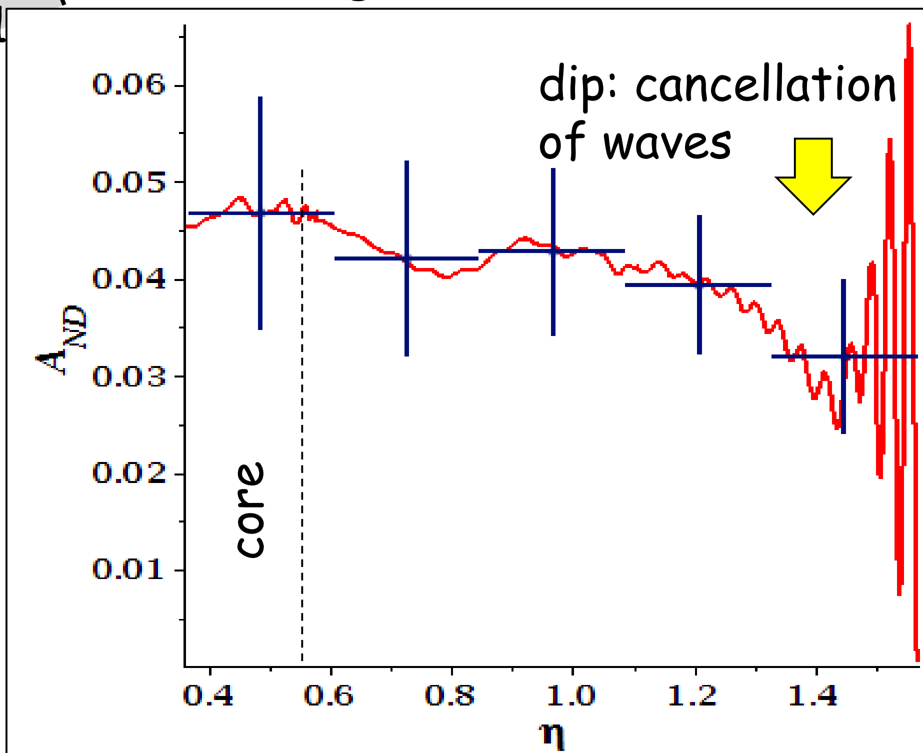
Three layer case: first layer prepare incoherent states:
applications for flavor – flavor transitions

Scanning the Earth

A. Ioannisian, A. Smirnov, D. Wyler, Phys.Rev. D96 (2017) no.3, 036005 arXiv:1702.06097 [hep-ph]



Integration above 11 MeV

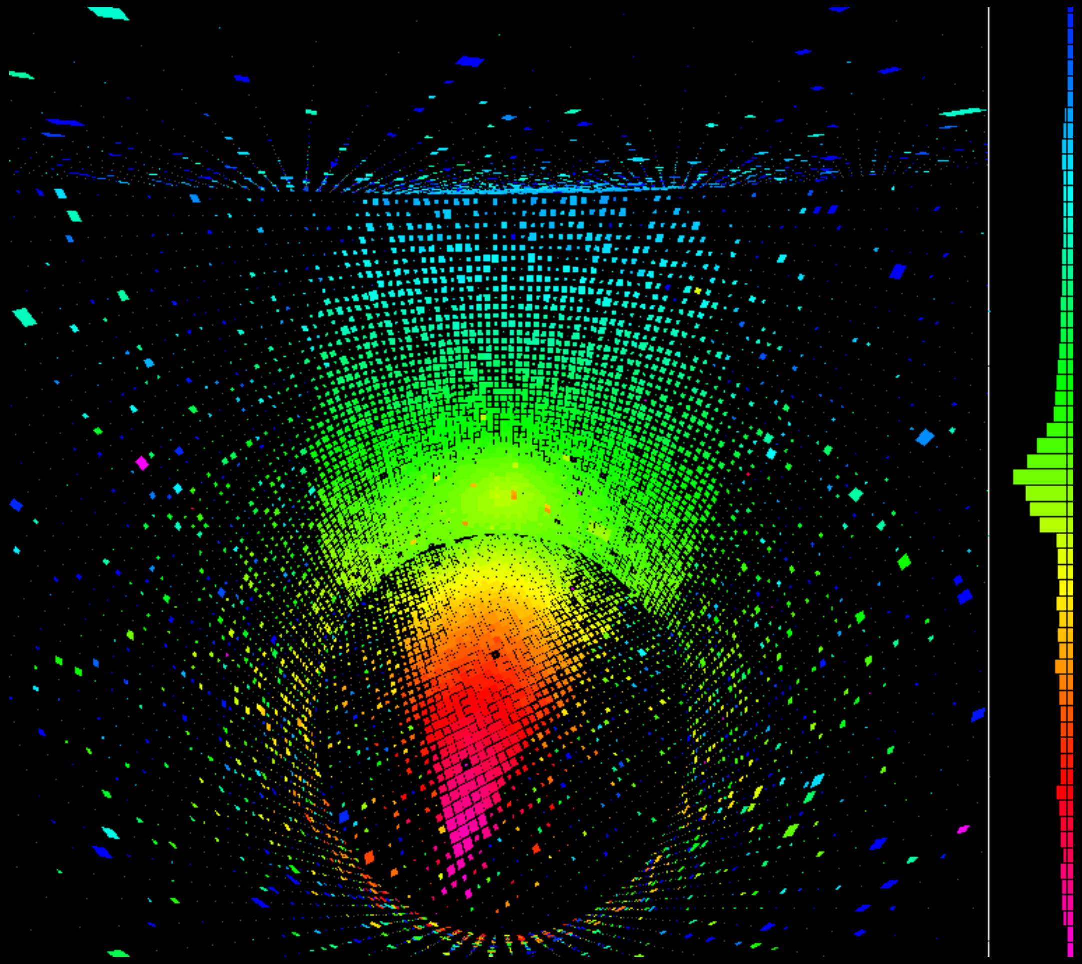


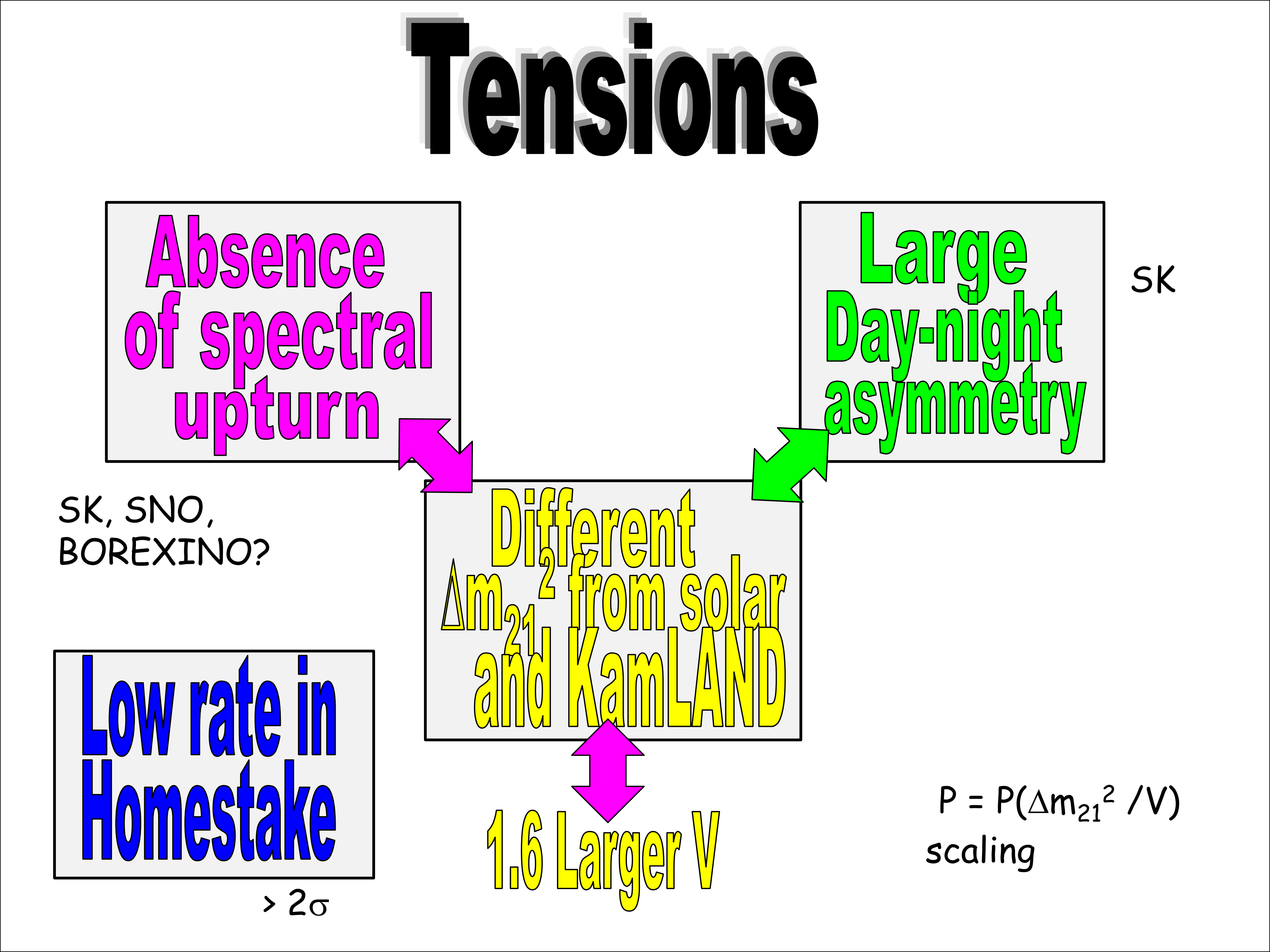
Day –Night asymmetry

$$A_{DN} = \frac{N(\eta)}{D} - 1$$

nadir angle →

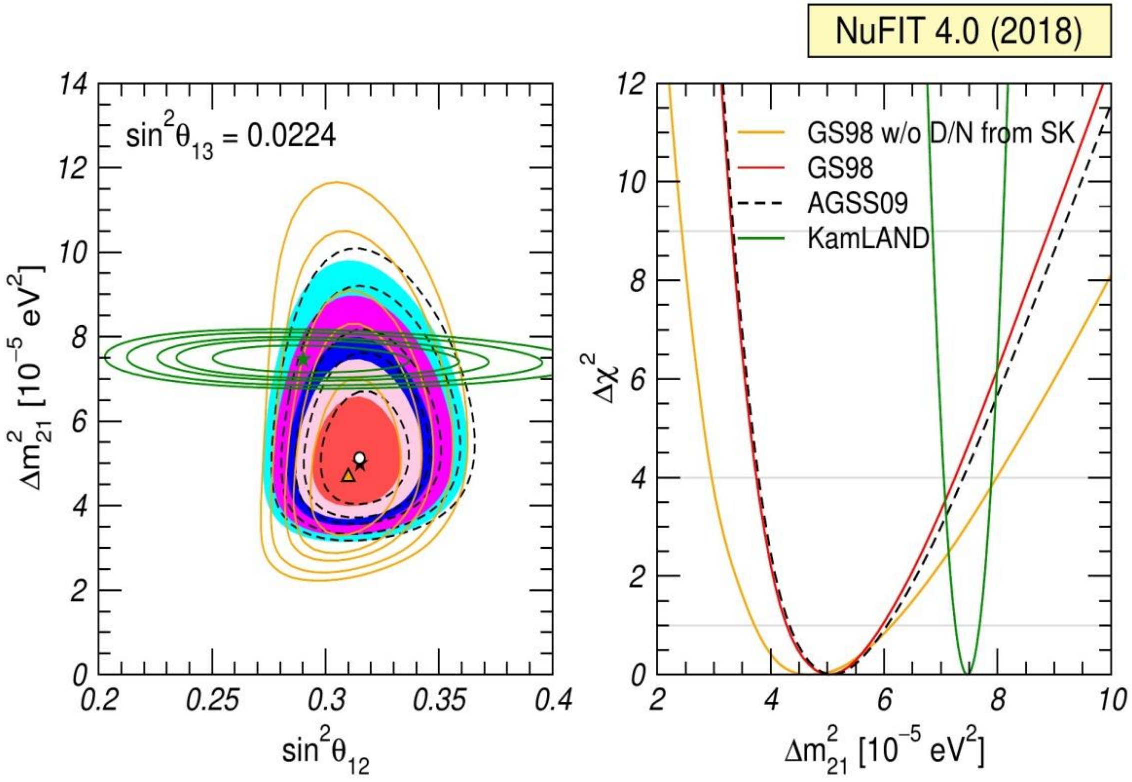
Solar -KM tension and new physics





Tensions
Absence of spectral upturn
SK, SNO, BOREXINO?
Large Day-night asymmetry
SK
Different Δm_{21}^2 from solar and KamLAND
Low rate in Homestake
> 2σ
1.6 Larger V
$P = P(\Delta m_{21}^2 / V)$ scaling

Solar neutrinos: Δm_{21}^2 - tension



Origin of tension:
- Absence of the upturn of spectrum (SNO, SK)
- 50% larger than expected D-N asymmetry for the bf Δm_{21}^2

Yellow lines - without the DN effect

68%, 90%, 95%, 99%, 3σ CL contours

Contours for solar models with different metallicity) also with and without DN effect

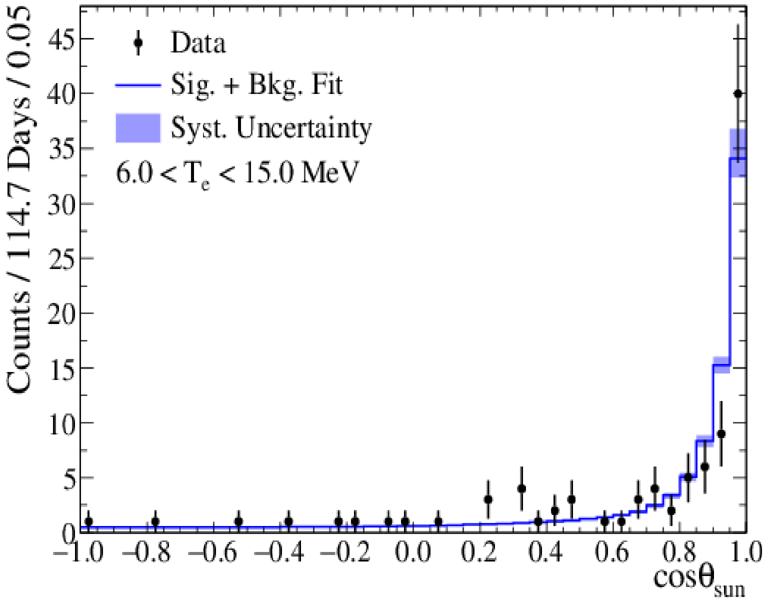
tension starts to disappear?

Solar neutrinos SNO+ results

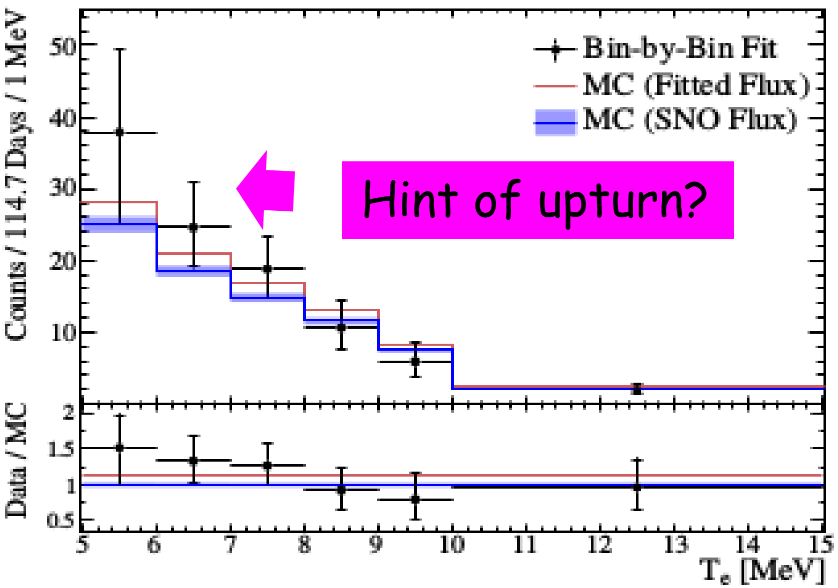
SNO+ Collaboration (Anderson, M. et al.)
Phys.Rev. D99 (2019) no.1, 012012
1812.03355 [hep-ex]

Water phase: Measurement of the 8B solar neutrino flux in SNO+ with very low backgrounds S/B ~ 4, E > 6 MeV

114.7 days of data



Distribution of event directions wrt. solar direction

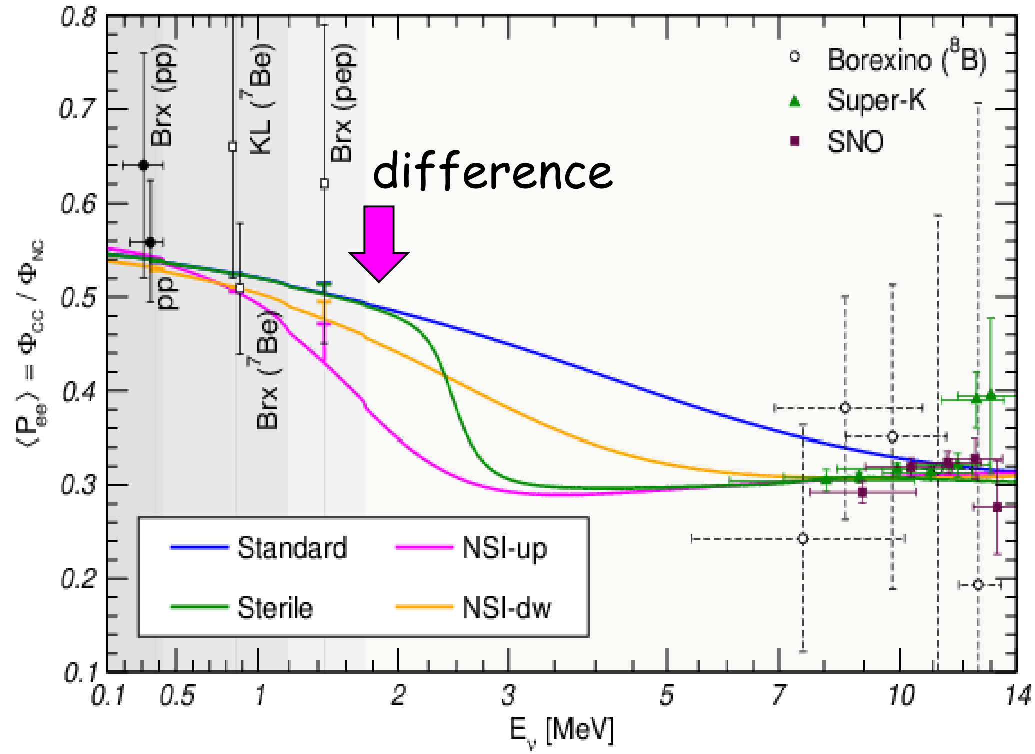


The extracted event rate as function of reconstructed electron kinetic energy

69.2 kt-day dataset

Flux: 2.53 [-0.28+0.31(stat) -0.10+0.13(syst)] x 10^{-6} cm $^{-2}$ s^{-1}

New physics effects



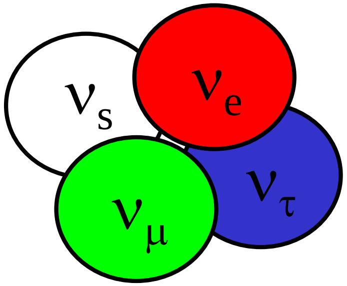
M. Maltoni, A.Y.S.
1507.05287 [hep-ph]

Extra sterile neutrino with $\Delta m^2_{01} = 1.2 \times 10^{-5}\ eV^2$, and $\sin^2 2\alpha = 0.005$

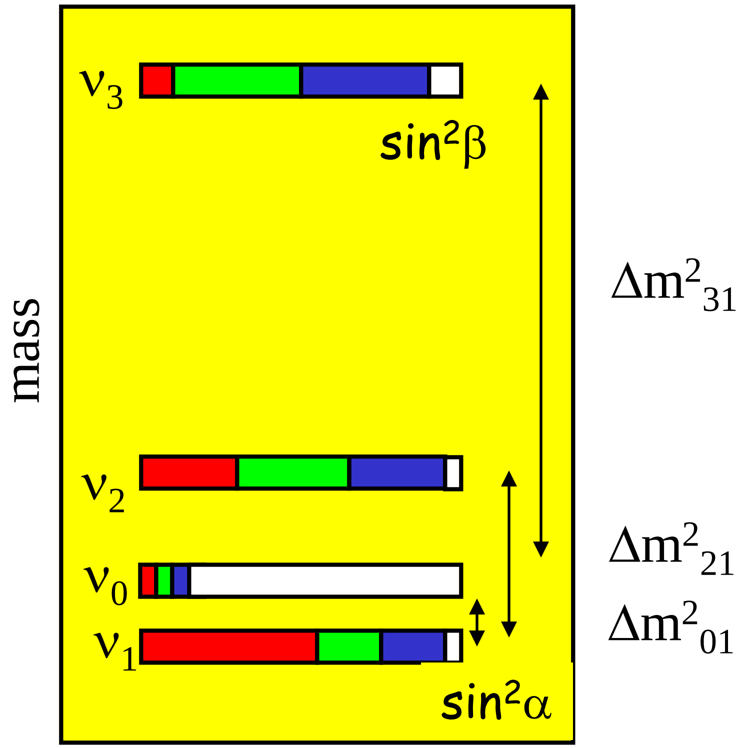
Non-standard interactions with
$\varepsilon^u_D = -0.22$, $\varepsilon^u_N = -0.30$
$\varepsilon^d_D = -0.12$, $\varepsilon^d_N = -0.16$

Also enhances the D-N asymmetry

meV sterile neutrino



sterile neutrino $m_0 \sim 0.003$ eV



For solar nu: $\sin^2 2\alpha \sim 10^{-3}$

Conversion for small mixing angle - Adiabaticity violation

Allows to explain absence of upturn and reconcile solar and KAMLAND mass splitting but not large D-N asymmetry

Additional radiation in the Universe

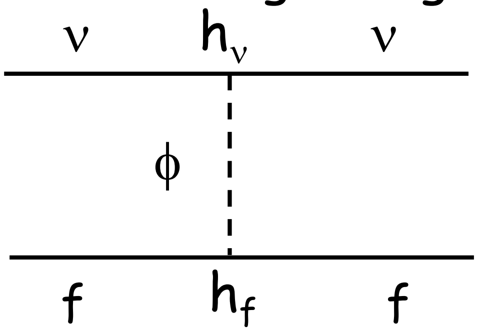
$\Delta N_{eff} \sim 0.1$

Searches for this sterile in atmospheric neutrinos if mixes with ν_3

Refraction due to long range forces

Light dark sector scalars, vectors …

Scattering via light mediators exchange:



$$A \sim \frac{h_\nu h_f}{q^2 - m_\phi^2}$$

With decrease of m_ϕ and the same decrease of h

refraction $(q^2 = 0) \sim h_\nu h_f / m_\phi^2$ does not change

inelastic scattering is suppressed as $h_\nu h_f / q^2$

Refraction effects dominate at small m_ϕ

Potential $$\boxed{V = \frac{h_\nu h_f}{m_\phi^2} n_f}$$

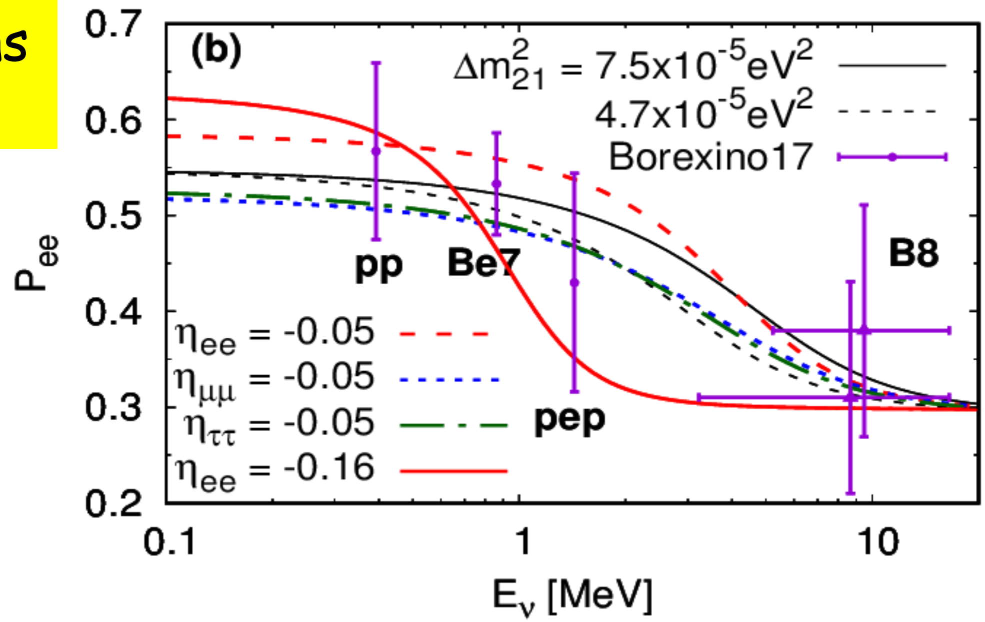
number density of scatterers

Refraction due to very light scalar mediator

Shao-Feng Ge, S. Parke, 1812.08376 [hep-ph]

Neutrino scattering on electrons via very light scalar exchange

The solar neutrino conversion probabilities with scalar NSIs vs. Borexino results.



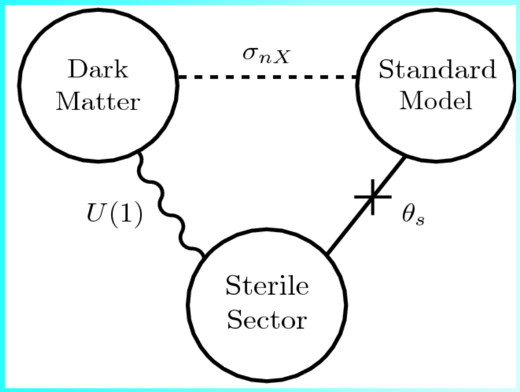
To satisfy bounds on h_ν h_e (especially from searches of 5th force:

$1/m_\phi \gg R_{Earth}$

→ strong suppression of the potential $V = V_0\, m_\phi R_{Earth}$

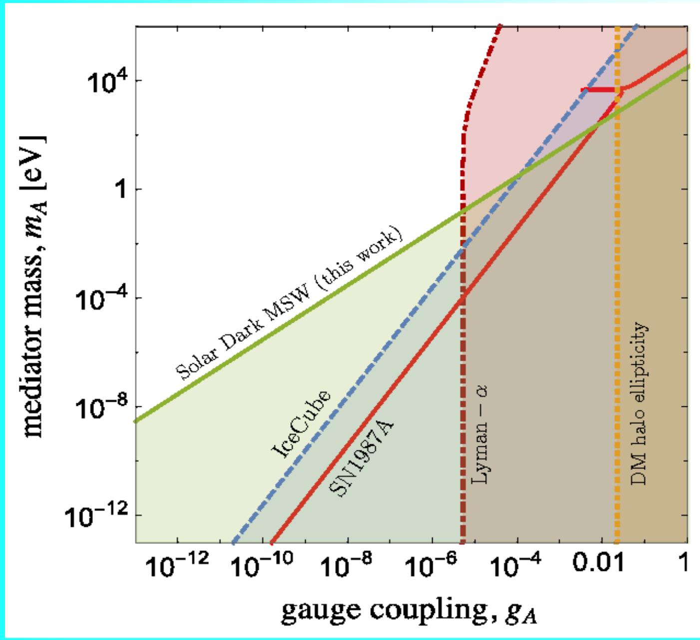
To avoid bounds – cancellations in 5th force experiments – not shown if this is possible

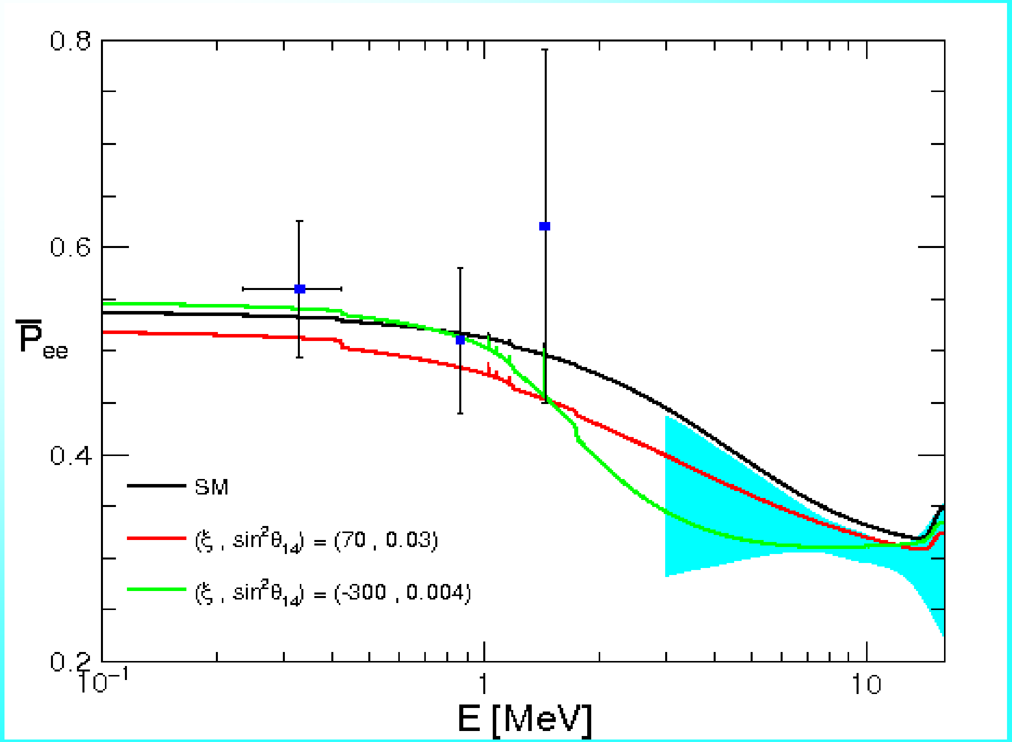
NSI on DM + mixing with sterile



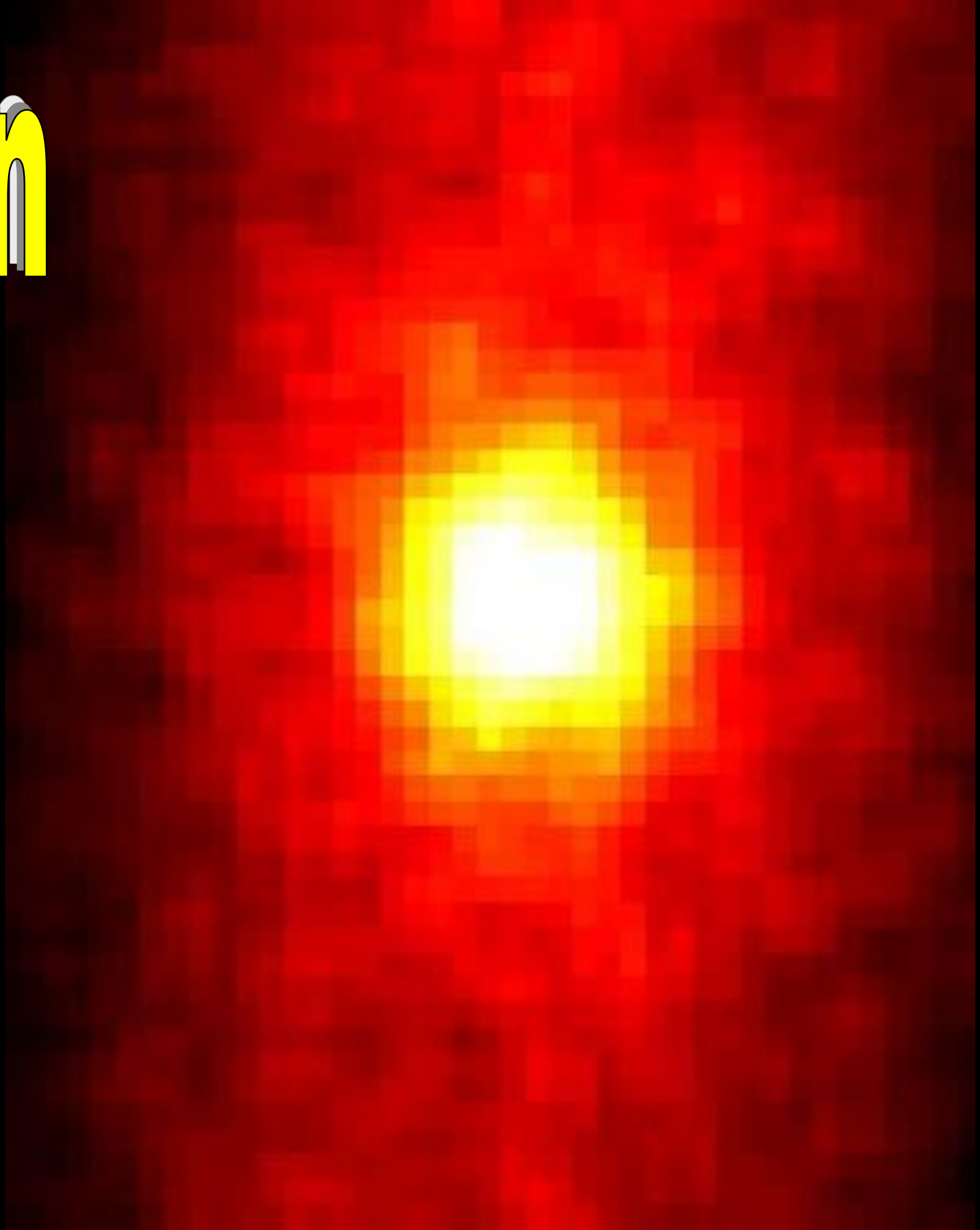
Solar Neutrinos as a Probe of Dark Matter-Neutrino Interactions - F. Capozzi, et al. JCAP 1707 (2017) no.07, 021 arXiv:1702.08464 [hep-ph]

$$\xi = \frac{G_X\, n_X(0)}{V_e(0)}$$ potential on DM





Conclusion



The MSW effect – adiabatic flavor conversion is driven by change of mixing angle in matter with density

It is realized inside the Sun

Oscillations are effect of change with distance phase difference between the eigenstates

Future: detailed study of oscillations in the Earth - interesting physics (multilayer medium, parametric effects, interference of waves "emitted from different borders between layers", attenuation. Potentially: tomography of the Earth

"Standard set" of non-standard physics

Steriles *

NSI *

Interactions with DM

Decays

Magnetic moments W

Decoherence

ν_{sun}

Long range forces

Violation of fundamental symmetries

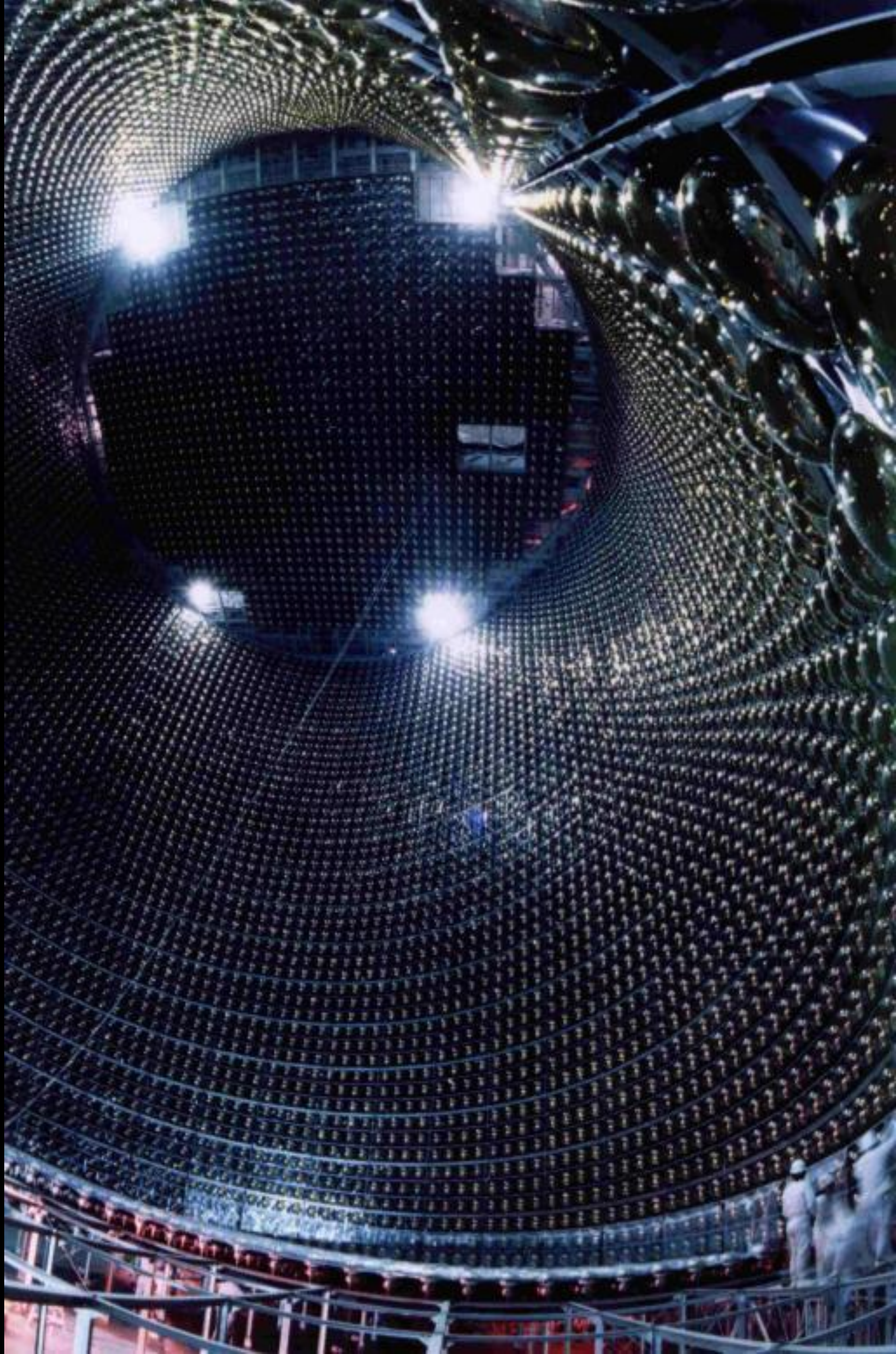
Lorentz CPT

~ E^n

W

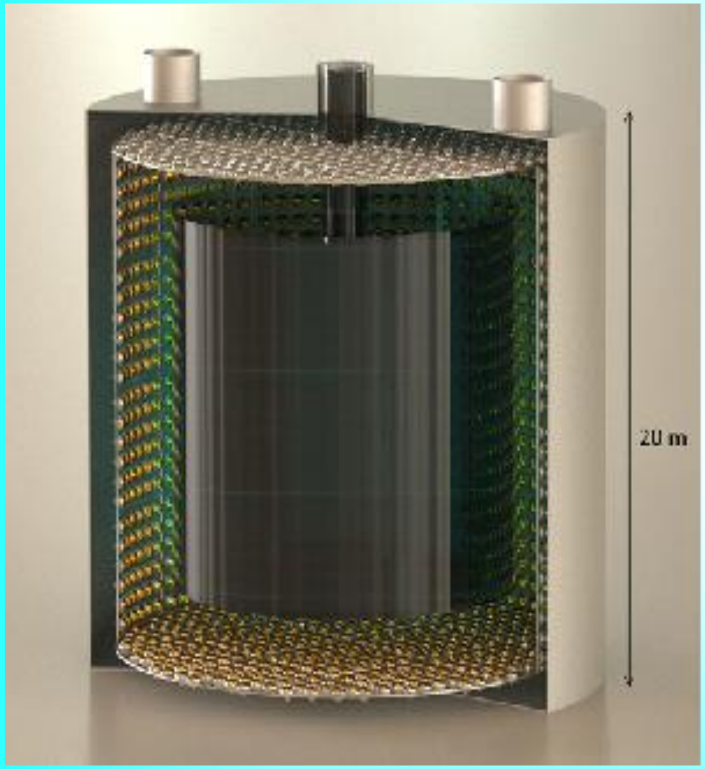
* - motivated by the present tensions

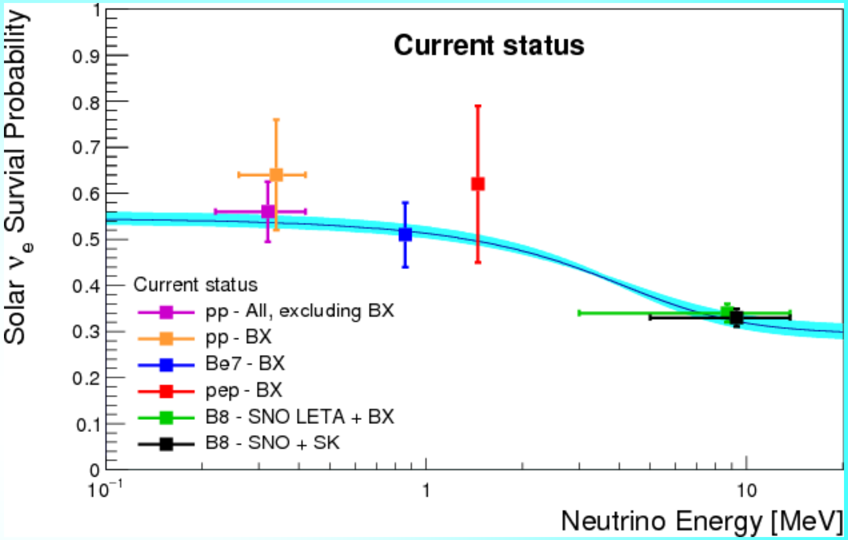
Attenuation effect

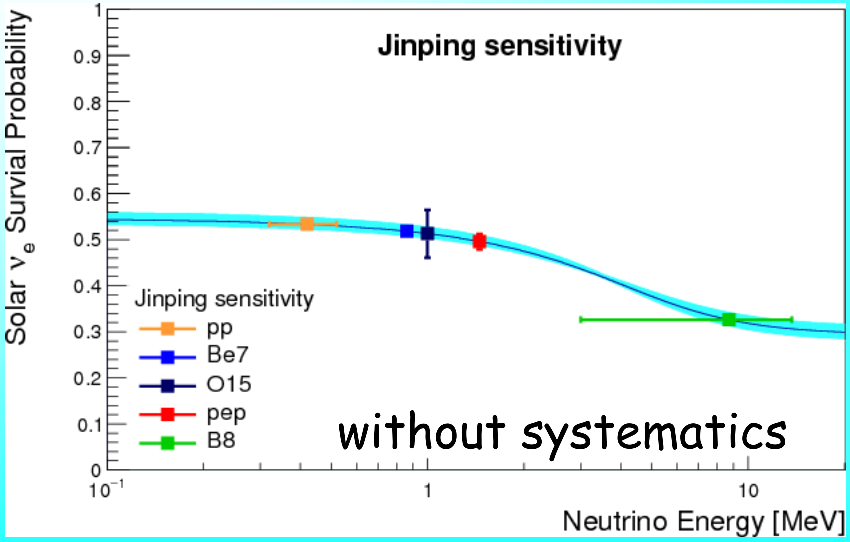


JinPing underground lab

scintillator uploaded
water detectors?







FV: 100 times bigger than
BOREXINO

Deeper than SNO

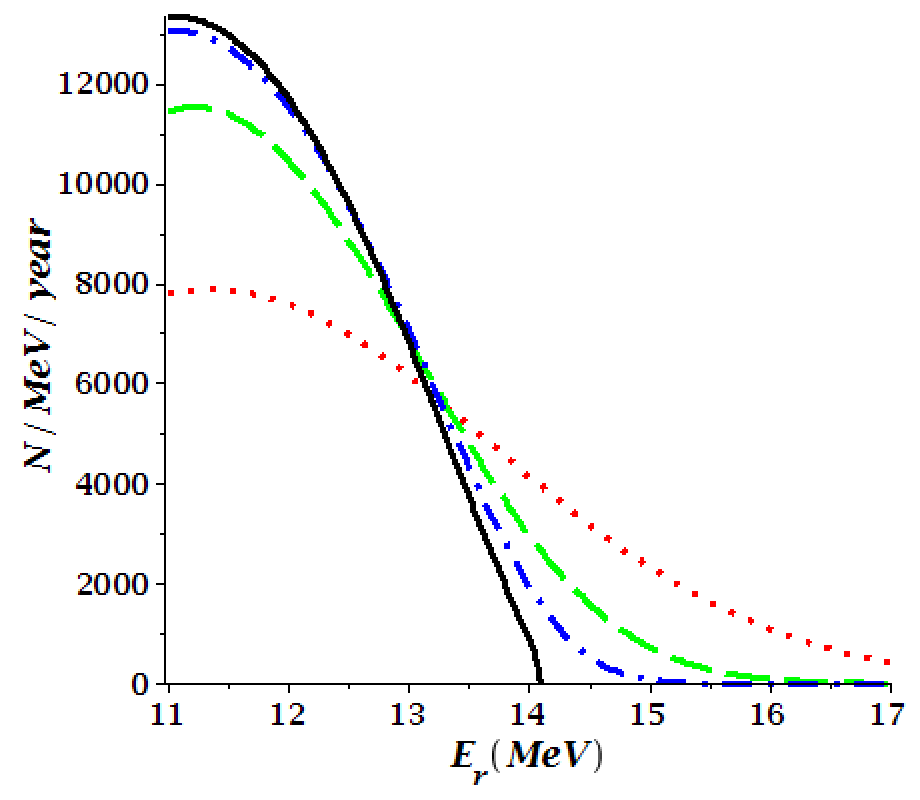
References

A. Ioannisian, A. Smirnov, D. Wyler,
Phys.Rev. D96 (2017) no.3, 036005
arXiv:1702.06097 [hep-ph]

A.N. Ioannisian, A. Yu. Smirnov
Phys.Rev. D96 (2017) no.8, 083009
arXiv:1705.04252 [hep-ph]

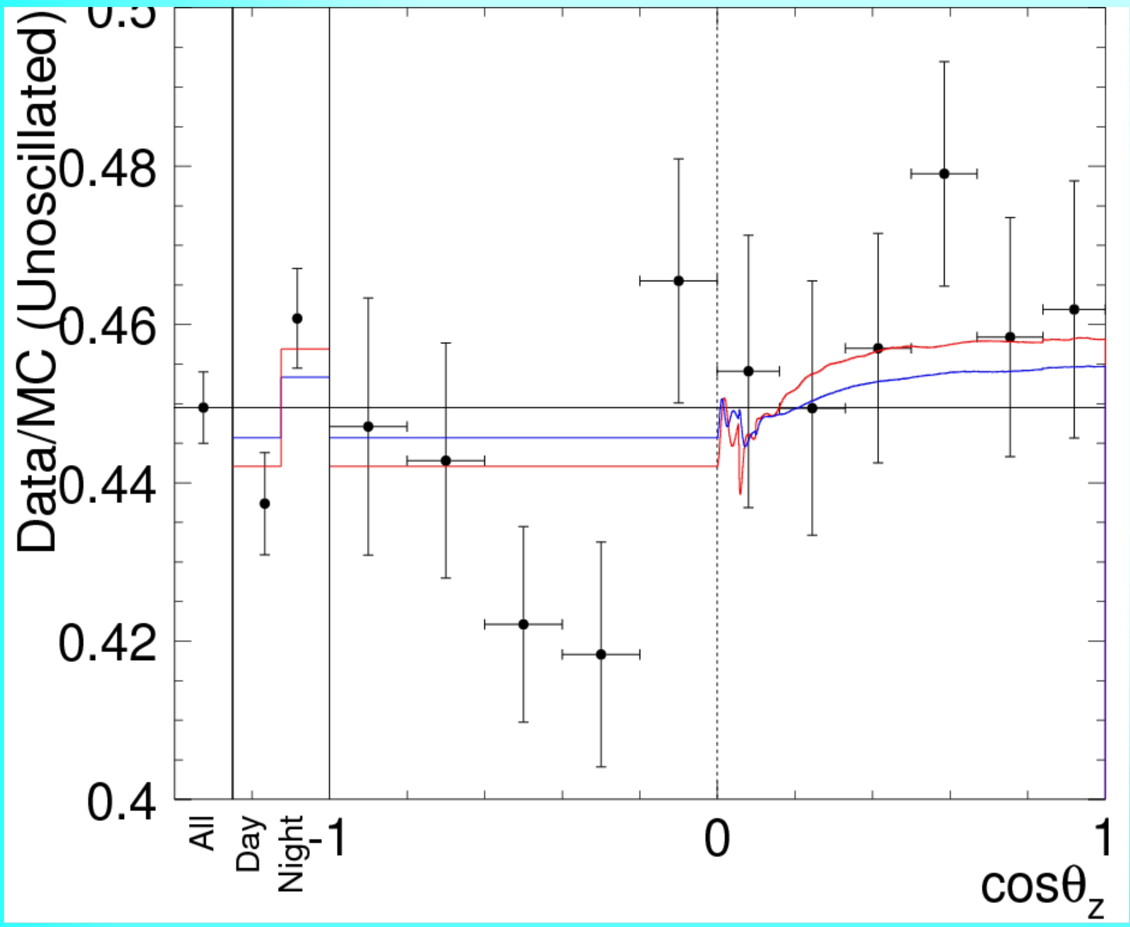
DUNE solar neutrino events

A. Ioannisian, A. Smirnov, D. Wyler, Phys.Rev. D96 (2017) no.3, 036005 arXiv:1702.06097 [hep-ph]



The energy (*ER*) distribution of the annually detected events at DUNE for different energy resolutions *σE*. The solid (black) line represents perfect resolution, *σE*=0, the other lines correspond to *σE*=0.5 MeV - dash-dotted (blue) line, *σE*=1 MeV dashed (green) line, *σE*=2 MeV dotted (red) line. The distributions are normalized to annual number of events 27000 at *Er*> 11 MeV.

Day-Night asymmetry

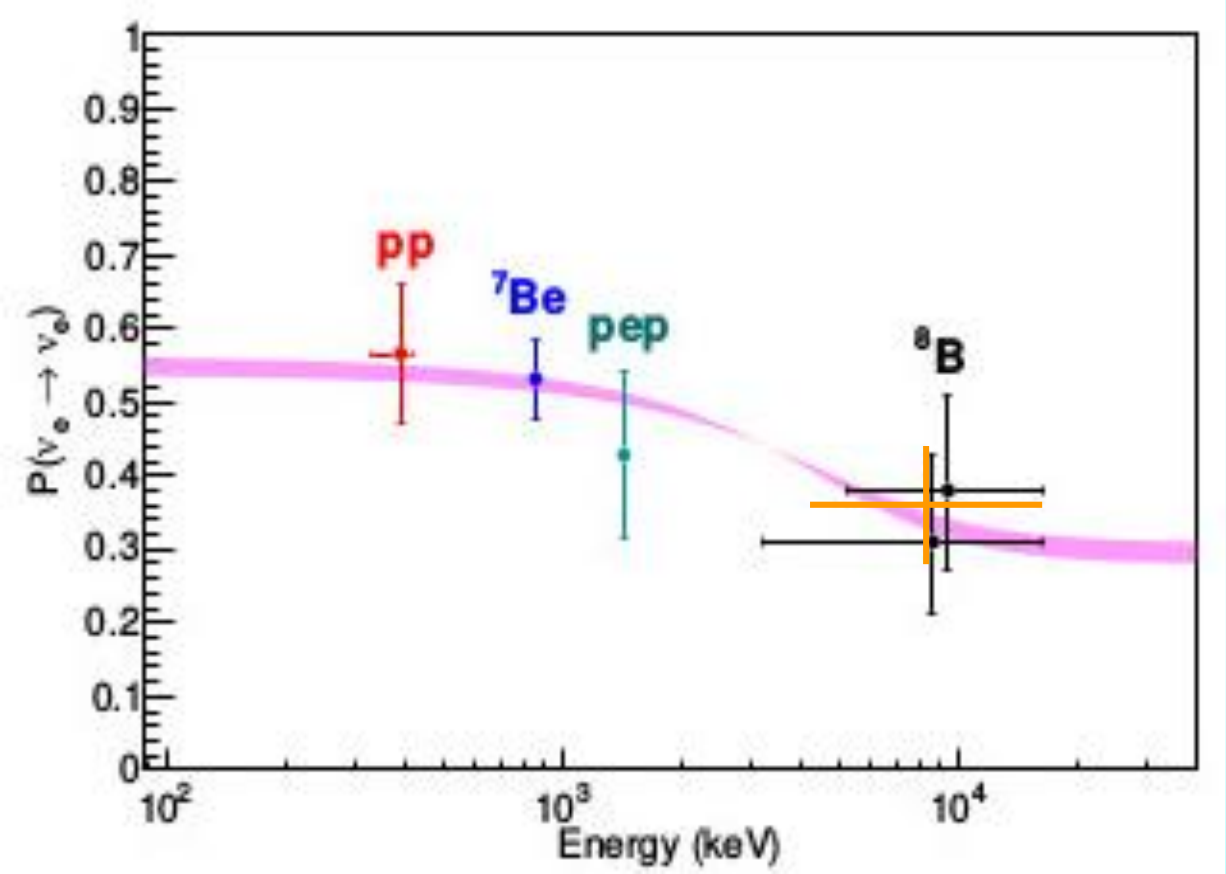


SK-IV solar zenith angle dependence of the solar neutrino data/MC (unoscillated) interaction rate ratio (4.49-19.5 MeV). Red (blue) lines are predictions when using the solar neutrino data (solar neutrino data+KamLAND) best-fit oscillation parameters. The error bars are statistical uncertainties only.

BOREXINO - Solar

Borexino Collaboration
(Agostini, M. et al.)
arXiv:1707.09279 [hep-ex]

G. Bellini
B. Caccianiga



Energy profile of the effect is determined by mixing in matter in production point + oscillations inside the Earth

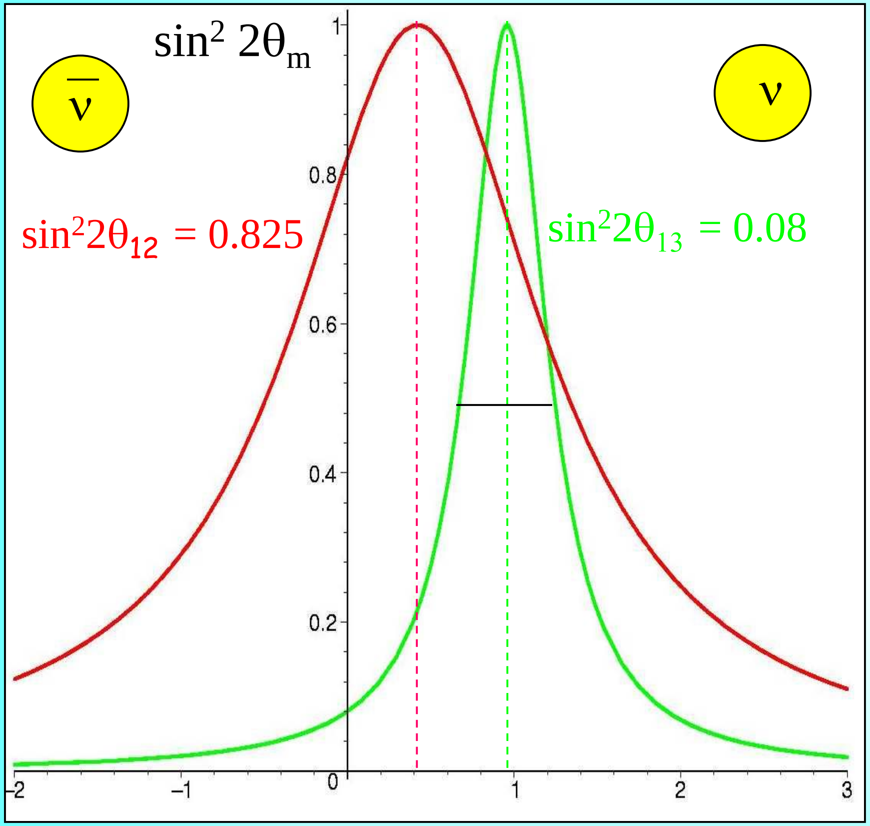
D. Franco

Scaring agreement

Problems in details
% level precision

Resonance

Dependence of mixing on density, energy has a resonance character



In resonance: $\sin^2 2\theta_m = 1$

Flavor mixing is maximal

$l_\nu = l_0 \cos 2\theta$

Vacuum oscillation length $\approx$ Refraction length

Resonance width: $\Delta n_R = 2 n_R \tan 2\theta$

density $l_\nu / l_0 \sim n E$

$\theta_m \to 0$ $\theta_m = \theta$ $\theta_m = \pi/4$ $\theta_m \to \pi/2$

Mixing is suppressed at high densities $|V| \gg \frac{\Delta m^2}{2E}$ $\Rightarrow$ Flavor states coincide with eigenstates and vice versa

Oscillations versus MSW

Adiabatic conversion

Different degrees of freedom involved

Oscillations

Vacuum or uniform medium with constant parameters

Phase difference increases between the eigenstates

$\phi(t)$

Mixing does not change

Adiabatic conversion

Non-uniform medium or/and medium with varying in time parameters

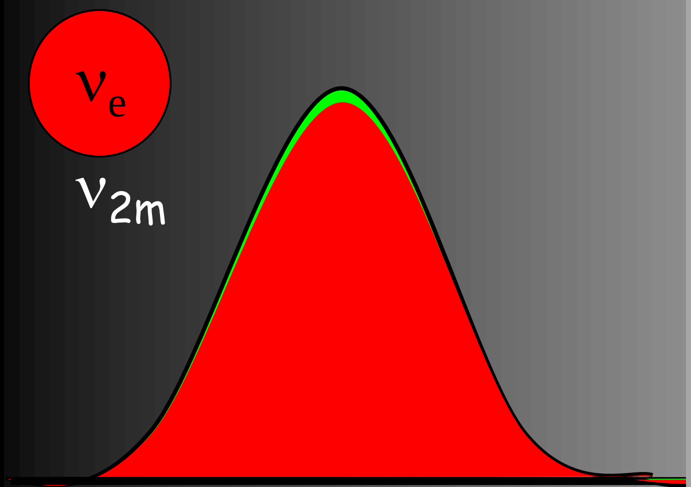
Change of mixing in medium → change of flavor of the eigenstates

$\theta_m(t)$

Phase is irrelevant

In non-uniform medium: interplay of both processes

Non-oscillatory transition



Single eigenstate:
→ no interference
→ no oscillations
→ phase is irrelevant

This happens when mixing is very small in matter with very high density

Adiabaticity

Adiabaticity condition $\left|\frac{d\theta_m}{dt}\right| \ll H_{2m} - H_{1m}$

External conditions (density) change slowly the system has time to adjust them

transitions between the neutrino eigenstates can be neglected $\nu_{1m} \not\leftrightarrow \nu_{2m}$ → The eigenstates propagate independently

Shape factors of the eigenstates do not change

Crucial in the resonance layer:
- the mixing changes fast
- level splitting is minimal

Adiabaticity condition $\Delta r_R > l_R$ if vacuum mixing is small

$\Delta r_R = n_R \tan 2\theta / (dn/dx)_R$

width of the resonance layer

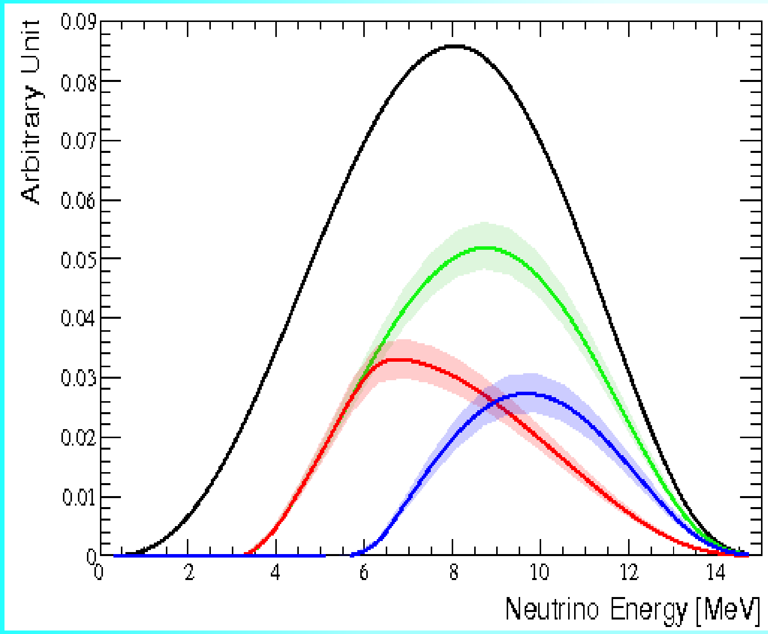
$l_R = l_\nu / \sin 2\theta$

oscillation length in resonance

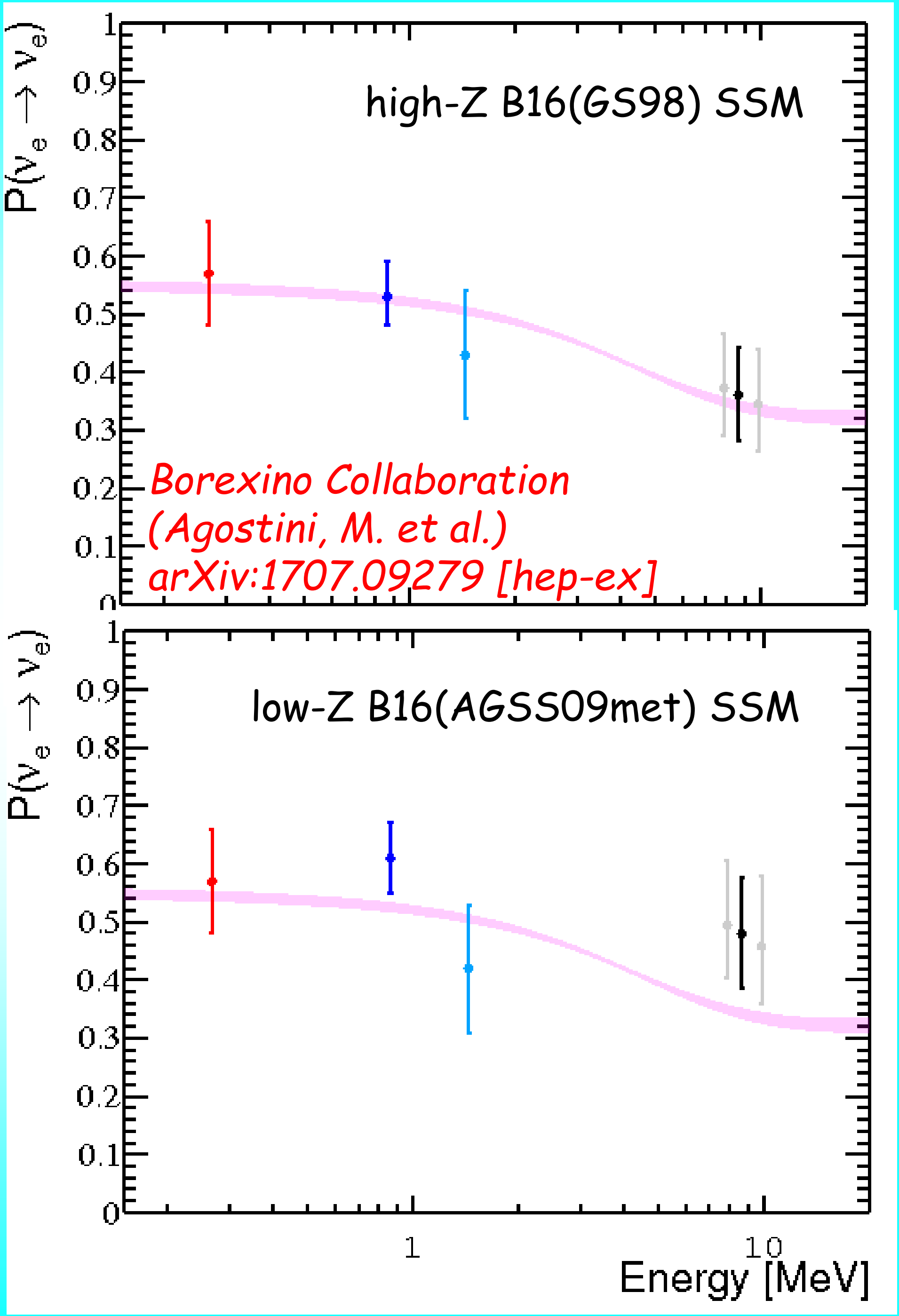
BOREXINO-II

8B spectrum with 1.5 kton y exposure

Borexino Collaboration
(Agostini, M. et al.) 1709.00756 [hep-ex]



the portions of the nu spectrum contributing to the LE (red), HE (blue), and LE+HE (green) energy windows used in the analysis.



Properties of LMA: scaling

Inside the Sun highly adiabatic conversion $\rightarrow$

the averaged survival probability is scale invariant = no dependence on distance, scales of the density profile, etc.

Function of the combinations

$$\epsilon_{12} = \frac{2VE}{\Delta m_{21}^2} \qquad \epsilon_{13} = \frac{2VE}{\Delta m_{31}^2}$$

Very weak dependence

With oscillations in the Earth

$$P_{ee} = P_{ee}(\epsilon_{12}, \epsilon_{13}, \phi_E)$$

$$\phi_E = \Delta m_{21}^2 L / 2E$$

L – the length of the trajectory in the Earth

If oscillations in the Earth are averaged

$$P_{ee} = P_{ee}(\epsilon_{12}, \epsilon_{13}) = P_{ee}(\epsilon_{12})$$

Invariance:

$$\Delta m_{ij}^2 \rightarrow a\, \Delta m_{ij}^2, \; V \rightarrow a\, V$$

$$\Delta m_{ij}^2 \rightarrow b\, \Delta m_{ij}^2, \; E \rightarrow b\, E$$

a = -1 flip of the mass hierarchy

Oscillation waves

~

$$P_{1e} = c_{13}^2 |S_{e1}|^2$$

due to transition to 3ν basis

Approximate (lowest order in ε) result

$$U_{k,k-1} \approx I - i\sigma_2 \sin \Delta\theta_{k-1}$$

Inserting this expression into formula for S and taking the lowest order terms in $\sin\Delta\theta_{k-1} \sim \varepsilon$

$$P_{1e} \sim c_{13}^2 \cos^2\theta_n^f + c_{13}^2 \sin 2\theta_n^f \, \Sigma_{j=0 \ldots n-1} \sin\Delta\theta_j \cos \phi_j^{after}$$

the 1-2 angle in matter near detector

sum over jumps

total phase acquired after jump j

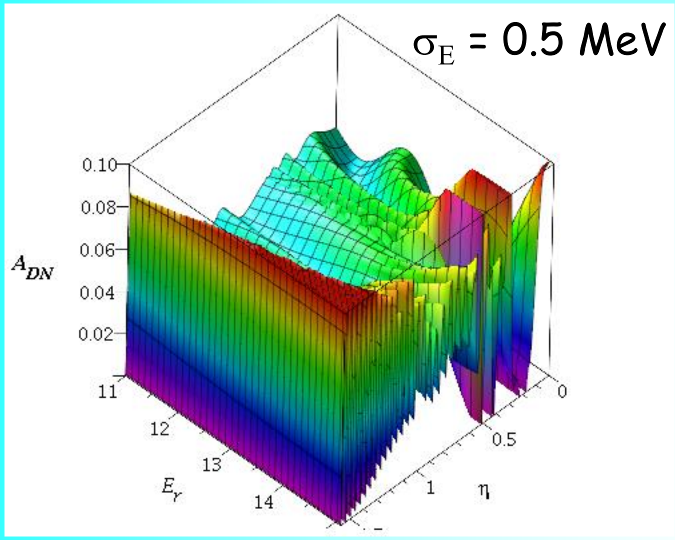
$$\sin \Delta\theta_j \simeq c_{13}^2 \sin 2\theta_{12} \Delta V_j \frac{E}{\Delta m_{21}^2}$$

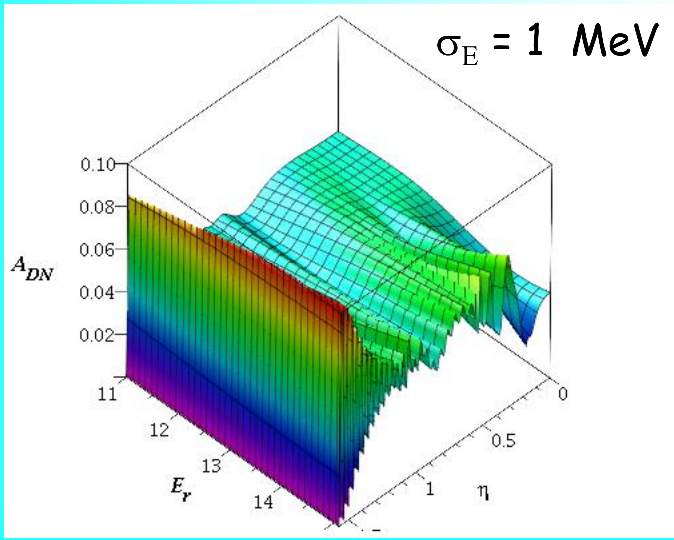
ΔV_j - j density jump

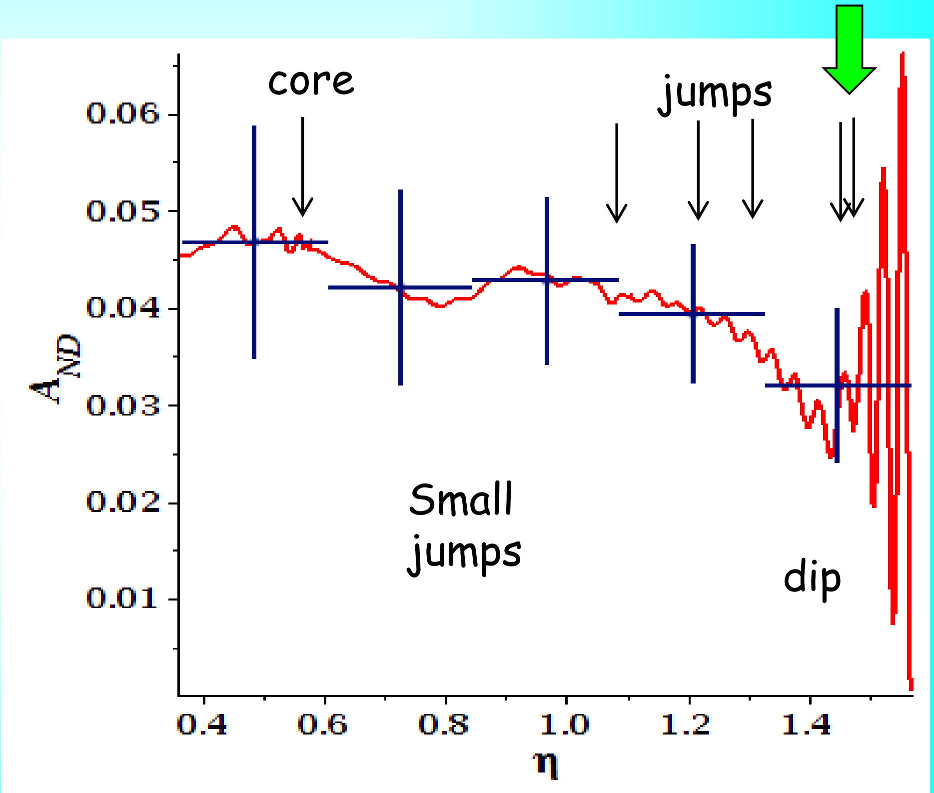
Relative D-N asymmetry

A. Ioannisian,
B. A.Y.S., D. Wyler
1702.06097 [hep-ph]

$$A_{DN} = \frac{N - D}{D}$$



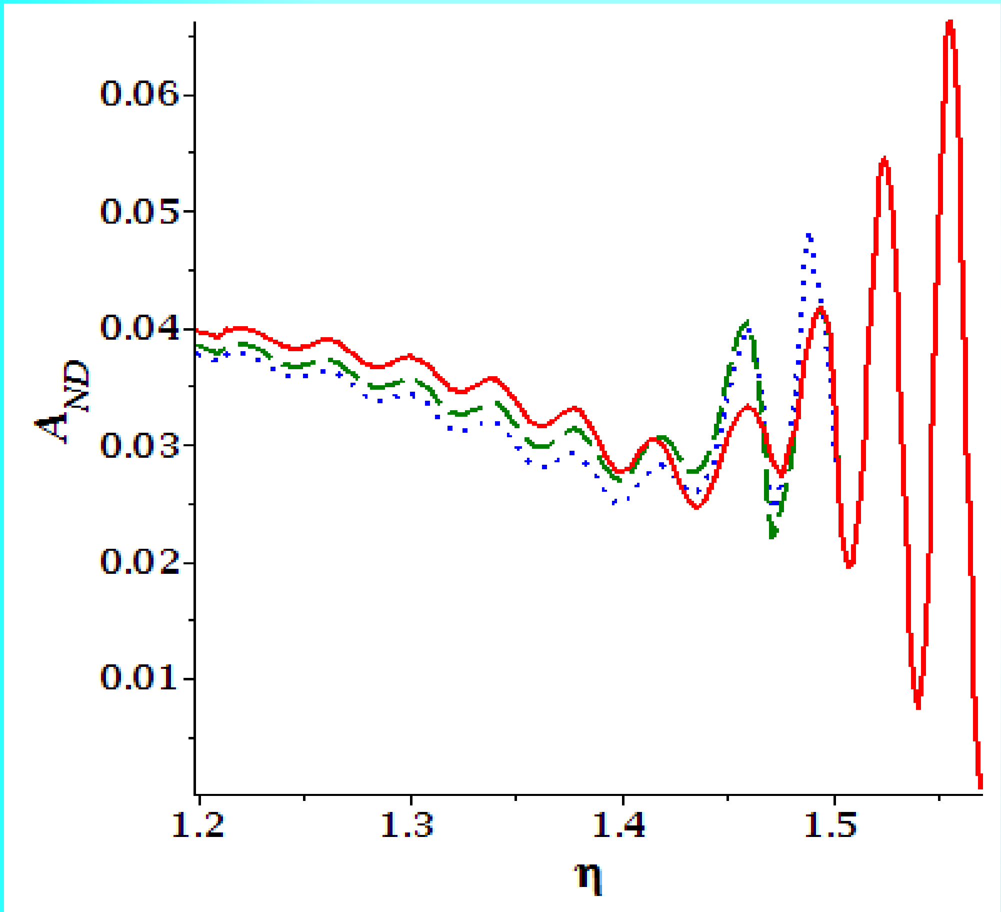




Relative excess of the night events
integrated over E > 11 MeV
Sensitivity of DUNE experiment
40 kt, 5 years

Tomography

A. Ioannisian, A. Smirnov, D. Wyler,
Phys.Rev. D96 (2017) no.3, 036005
arXiv:1702.06097 [hep-ph]



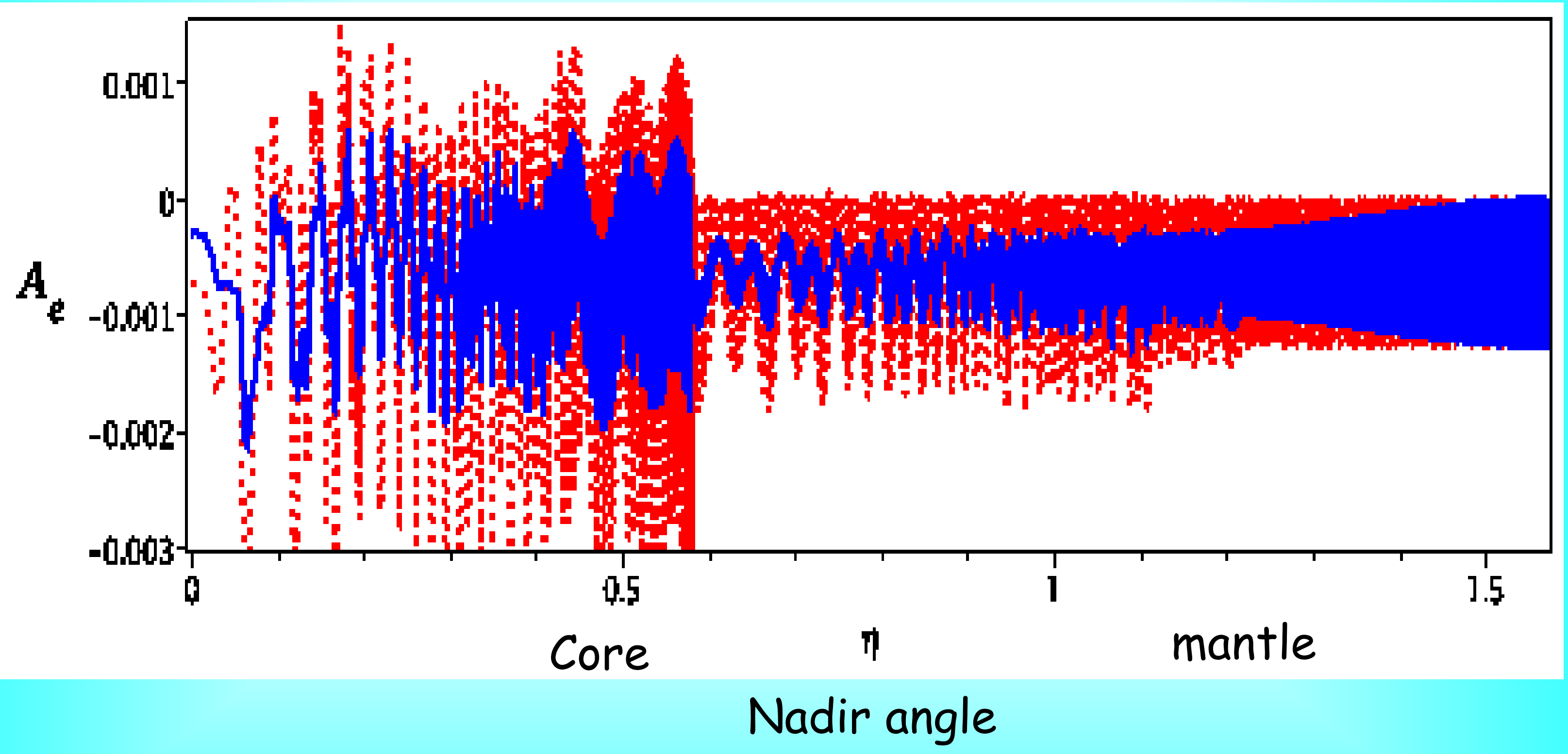
The relative excess of night events integrated over E > 11 MeV as function of the nadir angle for different positions of the density jumps. Jumps at

15 km and 25 km (red)
20.5 km and 30 km (blue dotted)
15 km and 30 km (green-dashed).

Parametric enhancement of oscillations is seen in the 3rd and 4th periods.

Variations of the ν_{Be} - flux

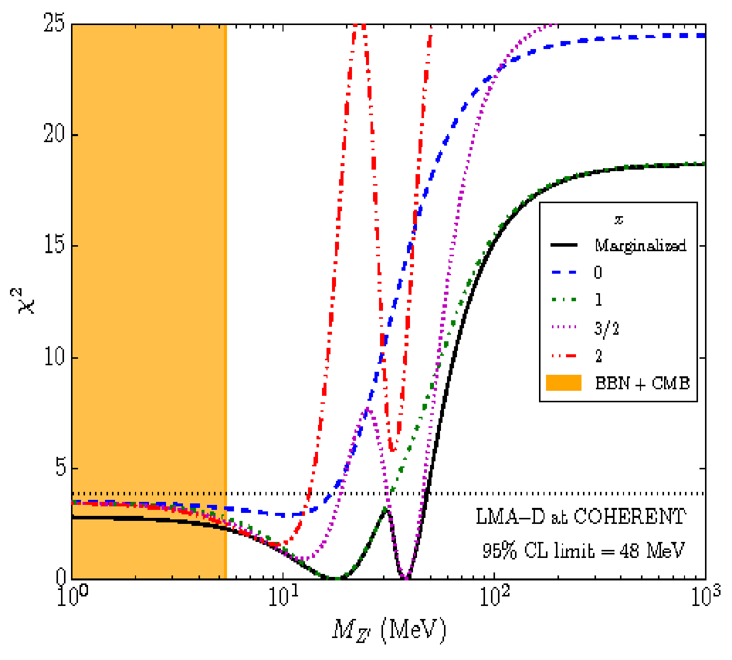
A. Ioannisian, AYS

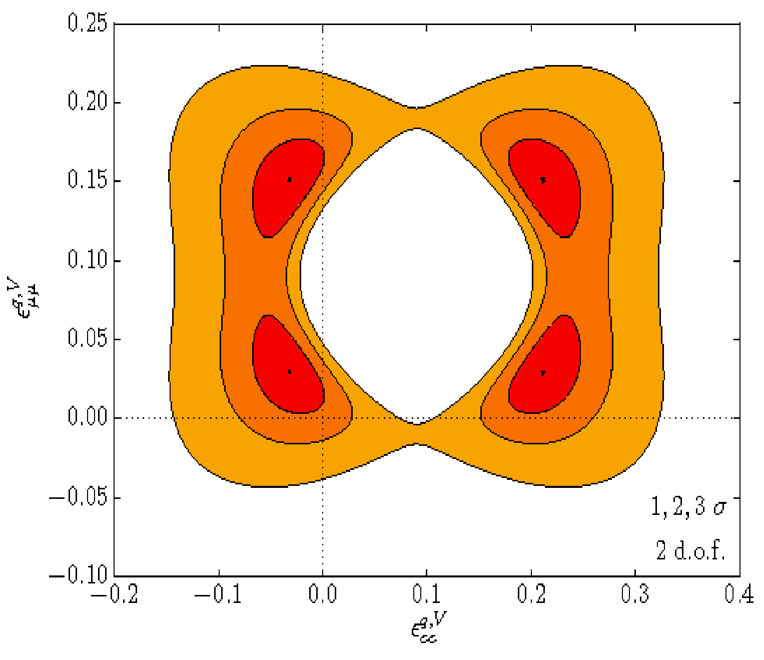


Again 0.1% effect

LMA-D

A Plan to Rule out Large Non-Standard Neutrino Interactions After COHERENT Data Denton, Peter B. et al. arXiv:1804.03660 [hep-ph]



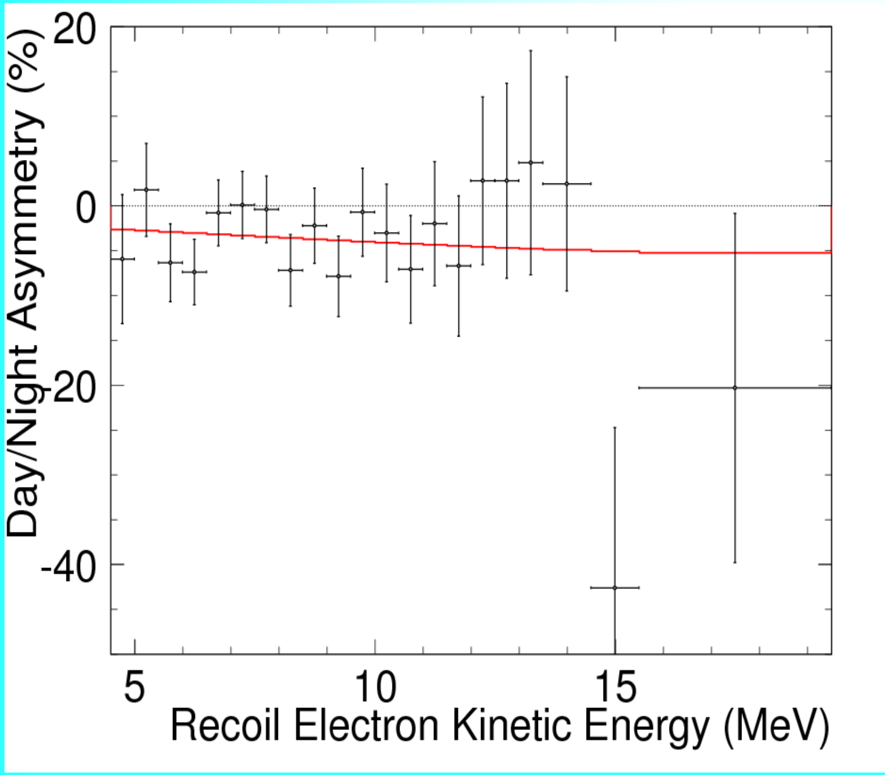


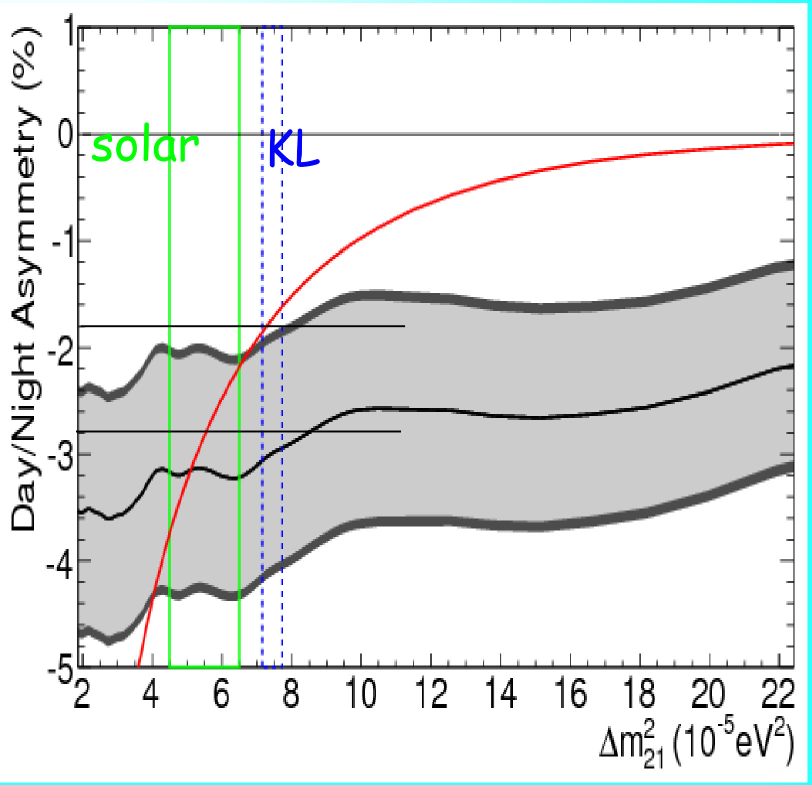
Day-Night effect

First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation

Super-Kamiokande collaboration (Renshaw, A. et al.) Phys.Rev.Lett. 112 (2014) 091805 arXiv:1312.5176

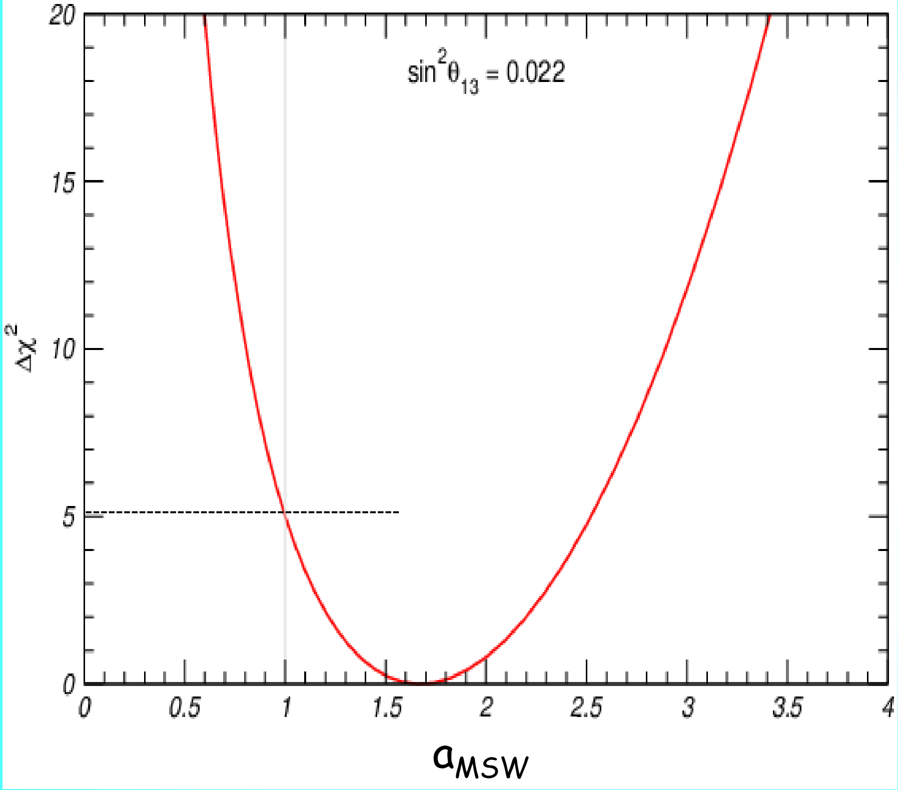
> 3 σ





Matter potential

G. L Fogli et al hep-ph/0309100
C. Pena-Garay, H. Minakata, hep-ph 1009.4869 [hep-ph]
M. Maltoni, A.Y.S. 1507.05287 [hep-ph]



$V = a_{MSW} V_{stand}$

$a_{MSW} = 0$ is disfavoured by $> 15\ \sigma$

the best fit value $a_{MSW} = 1.66$

$a_{MSW} = 1.0$ is disfavoured by $> 2\ \sigma$

related to discrepancy of Δm^2_{21} from solar and KamLAND:

$$\frac{\Delta m^2_{21}\,(KL)}{\Delta m^2_{21}\,(Sun)} = 1.6$$

Determination of the matter potential from the solar plus KamLAND data using a_{MSW} as free parameter

Potential enters the probability in combination

$$\frac{V}{\Delta m^2_{21}}$$

Hamiltonian in matter

$$H(n_e, E) = H_0 + V$$

$$V = \mathrm{diag}\,(V_e\ ,\ 0, 0\ )$$

In the flavor basis $(\nu_e\ , \nu_\mu)^T$

$$H_{tot} = \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta + \xi & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

$$\xi = \frac{4V_e E}{\Delta m^2} \qquad V_e = \sqrt{2}\, G_F n_e$$

Adiabaticity

For varying density – another degree of freedom: eigenstates composition of a given propagating state

It can change which is related to transitions

$\nu_{1m} \Leftrightarrow \nu_{2m}$

Efficiency of the transitions is determined by the degree of adiabaticity.

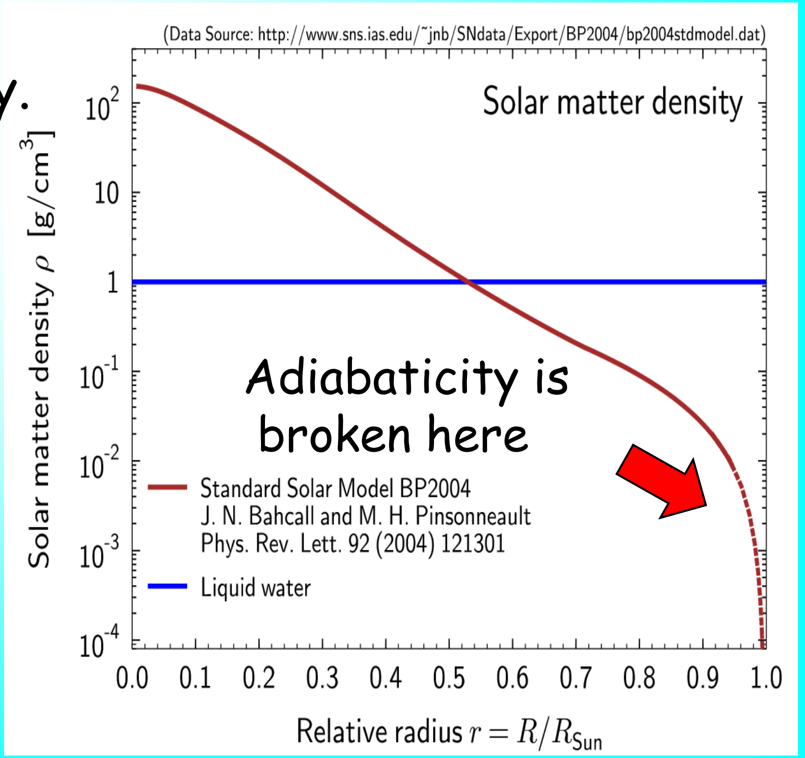
If density changes slowly enough, so that

$$\left| \frac{d\theta_m}{dt} \right| \ll H_{2m} - H_{1m}$$

Difference of ehgenvalues

"adiabaticity condition"

The transitions between eigenstates can be neglected

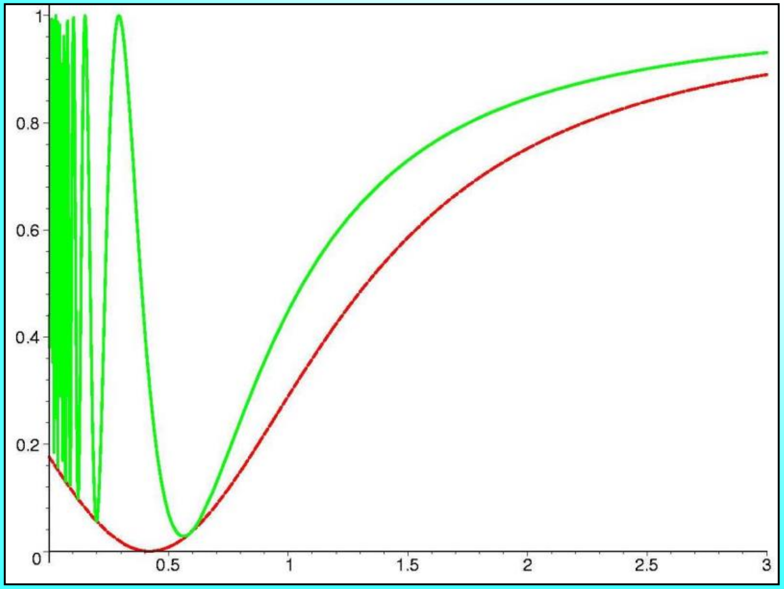


Two realizations

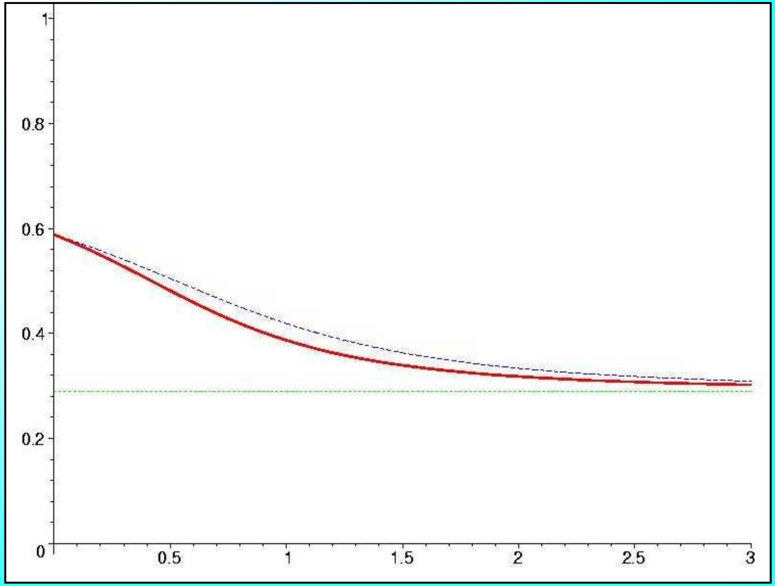
Constant density	Slowly changing density
Different E	Fixed E
Resonance enhancement of oscillations	Adiabatic flavor conversion

ν

$\frac{F(E)}{F_0(E)}$



E/E_R



E/E_R

Properties of LMA: scaling

$P_{ee} = P_{ee}(\theta_m^0)$ (day)

$$\theta_m^0 = \theta_m^0 \left(\theta, \frac{2VE}{\Delta m_{21}^2}\right)$$

Invariance: $\Delta m_{21}^2 \rightarrow a\, \Delta m_{21}^2, \quad V \rightarrow a\, V$

P_{ee} is scale invariant - no dependence on distance, scales of density profile

a = -1 flip of the mass hierarchy implies the change of sign of V

(NSI)

Oscillations in the Earth break scaling: phase

$$\phi_E = \frac{\Delta m_{21}^2 L}{2E}\, f\left(\frac{2VE}{\Delta m_{21}^2}\right)$$

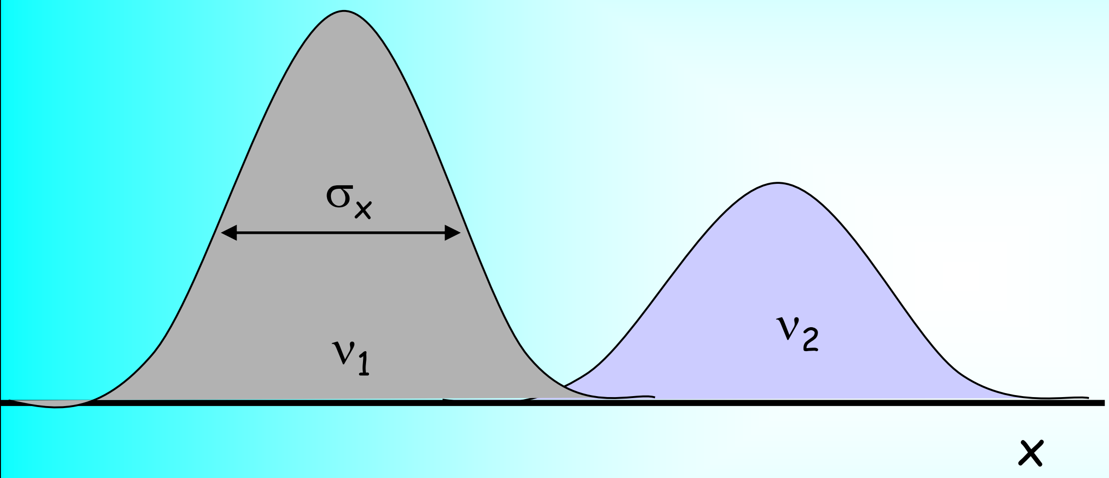
L – the length of the trajectory in the Earth

If oscillations in the Earth are averaged (valid for the present accuracy) - the scaling is restored

Also invariance $\Delta m_{ij}^2 \rightarrow b\, \Delta m_{ij}^2, \quad E \rightarrow b\, E$

Coherence in propagation

In the configuration space: separation of the wave packets due to difference of group velocities



$\Delta v_{gr} = \Delta m^2 / 2E^2$

separation: $\Delta v_{gr} L = \Delta m^2 L / 2E^2$

no overlap: $\Delta v_{gr} L > \sigma_x$

coherence length:

$L_{coh} = \sigma_x E^2 / \Delta m^2$

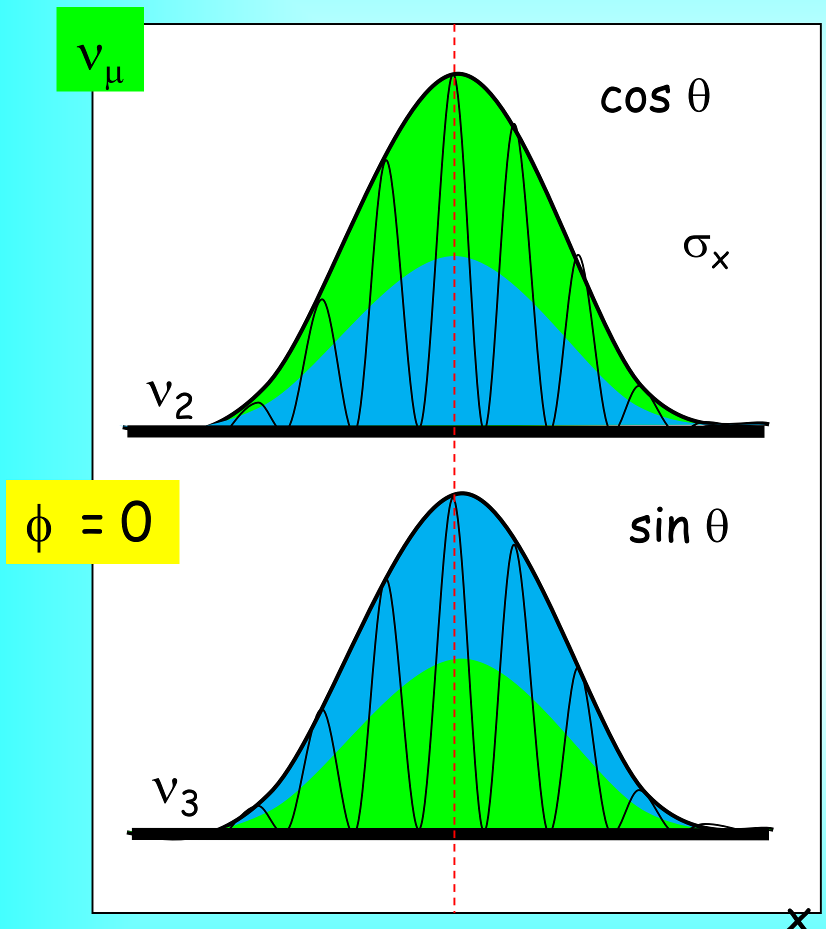
In the energy space: averaging over oscillations

Oscillatory period in the energy space $E^T = 4\pi E^2 / (\Delta m^2 L)$

Averaging (loss of coherence) if energy resolution σ_E is $E^T < \sigma_E$

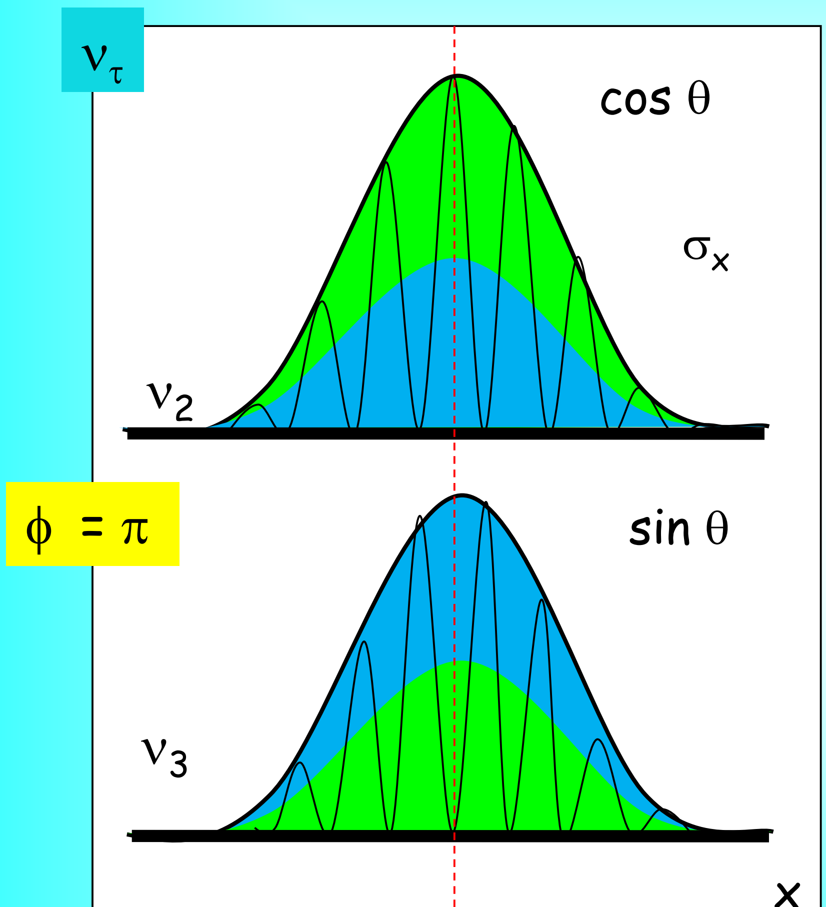
→ leads to the same coherence length

Oscillations



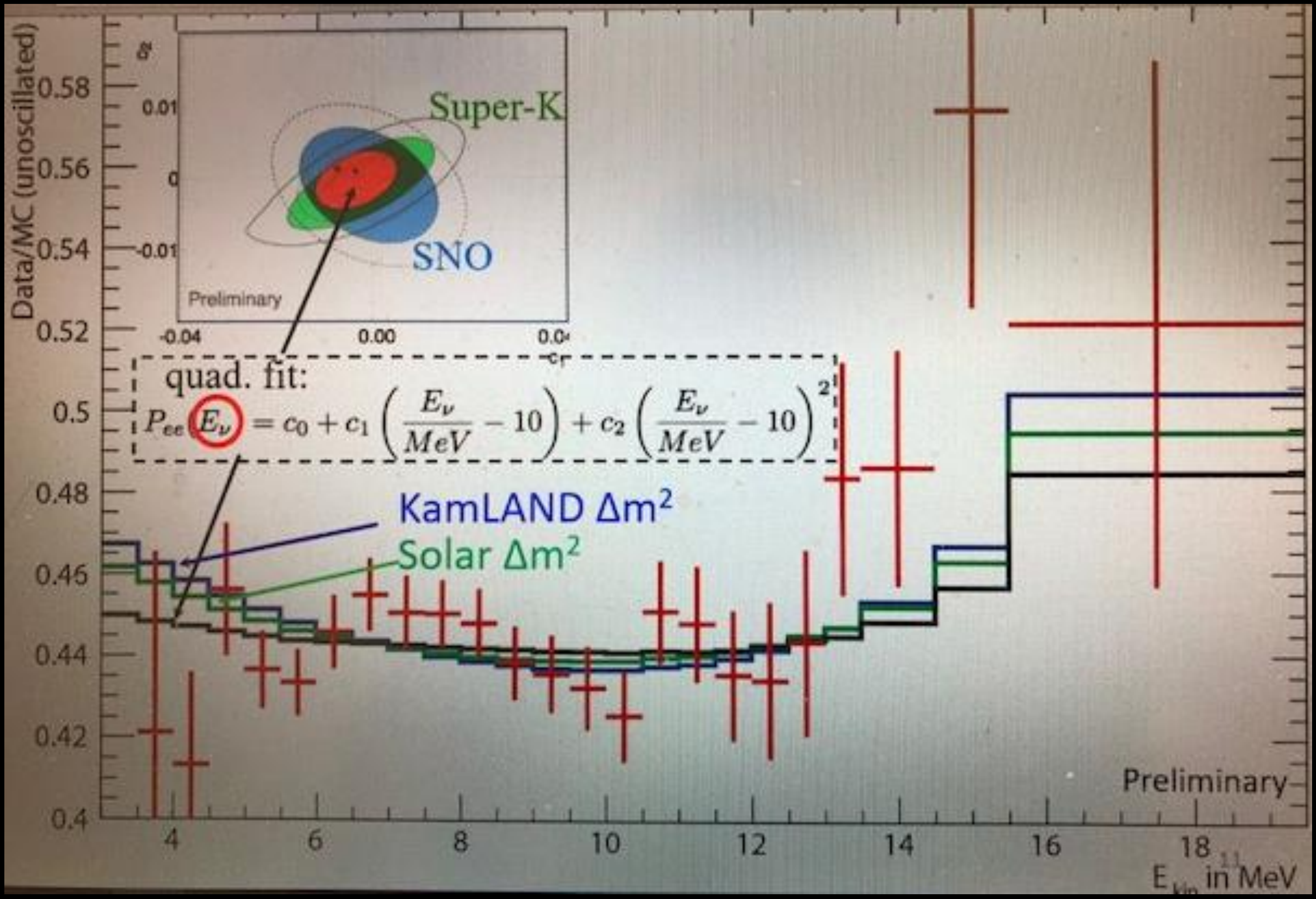
- Destructive interference of the tau parts
- Constructive interference of muon parts

Oscillations

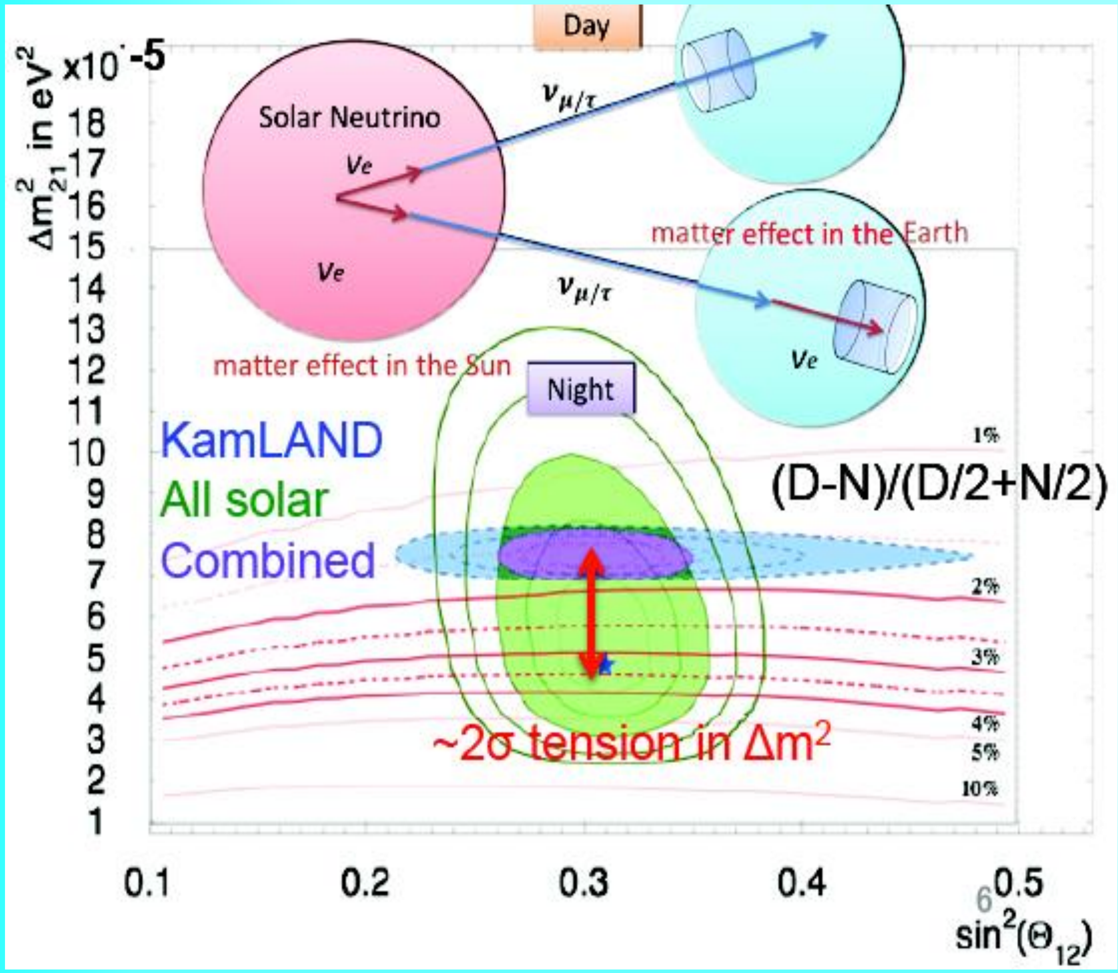


- Destructive interference of the muon parts
- Constructive interference of tau parts

Spectrum of all SK data



SK analysis



T. Yano. ICRC 2017

A_{DN} = -3.3 +/- 1.1 %

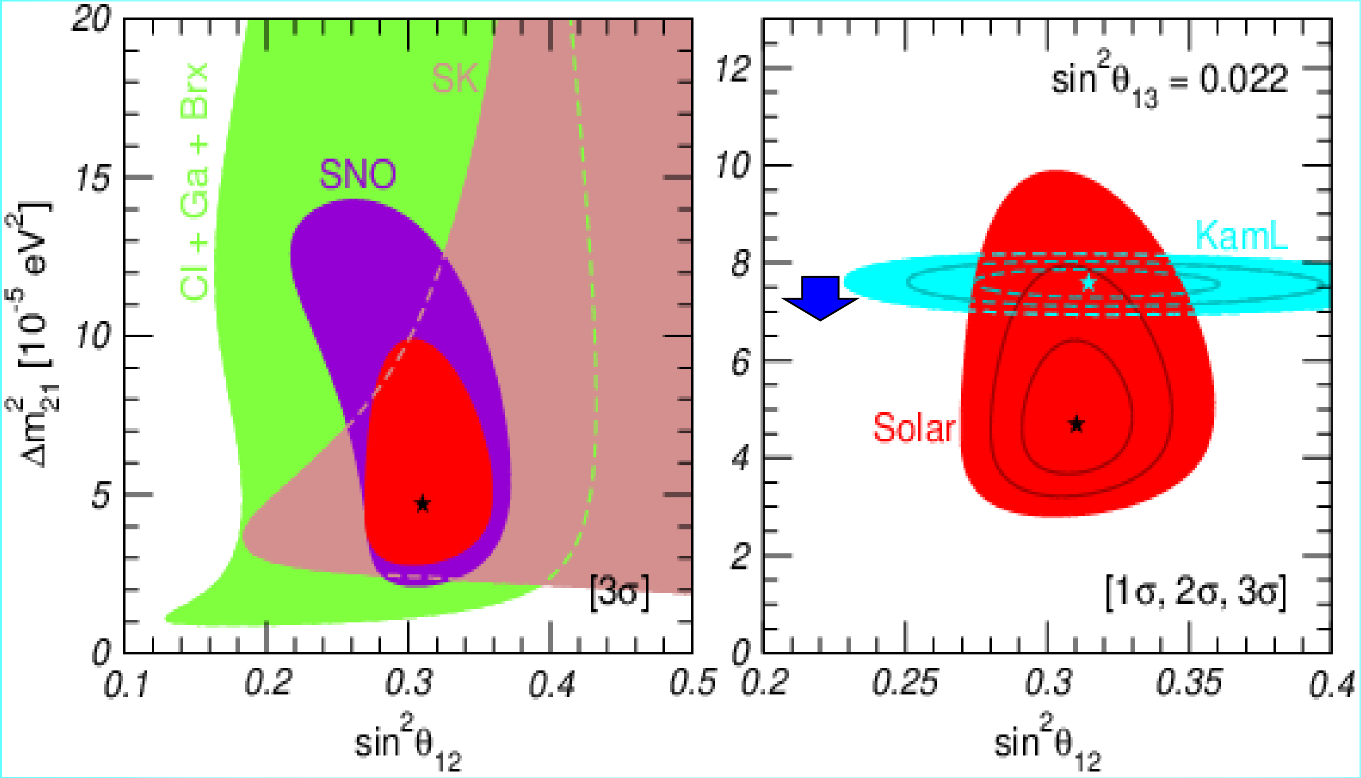
Expected for global mass difference

A_{DN} = -1.8%

M. Smy: improve Sensitivity to D-N Lower bkgr- increase F.V. for high energy Solar neutrinos

Neutrino parameters

M. Maltoni, A.Y.S.
1507.05287 [hep-ph]



Red: all solar neutrino data

Δm^2_{21} (KL) > Δm^2_{21} (solar)   2 σ

KamLAND data reanalized in view of reactor anomaly (no front detector) bump at 4 -6 MeV

Δm^2_{21} decreases by $0.15\ 10^{-5}$ eV^2

How things may develop

Solar value Δm_{21}^2 = 7×10^{-5} eV^2 (before 2010) was reduced after SK data on D-N asymmetry and measurements of spectrum

- JUNO: precise measurements of Δm_{21}^2 with (0.7 -1)% accuracy

$$\sigma(\Delta m_{21}^2) = (0.05 - 0.07)\times10^{-5}\ \mathrm{eV}^2$$

Difference of solar and KamLAND

$$\Delta(\Delta m_{21}^2) = 2.5\times10^{-5}\ \mathrm{eV}^2$$

If $\Delta m_{21}^2(\mathrm{JUNO}) = \begin{cases} \Delta m_{21}^2(\mathrm{solar}) & \text{problem solved} \\ \Delta m_{21}^2(\mathrm{KL}) & \text{problem sharpens} \end{cases}$

- Stronger bounds on NSI from COHERENT and other experiments
- SNO+ spectrum measurements above 3 MeV (testing upturn)
- Hyper-Kamiokande — Day-night asymmetry, spectrum
- DUNE

Adiabatic conversion probability

Sun, Supernova

Initial state: $\nu(0) = \nu_e = \cos\theta_m^0\, \nu_{1m}(0) + \sin\theta_m^0\, \nu_{2m}(0)$

Mixing angle in matter in production point

Adiabatic evolution to the surface of the Sun (zero density):

$\nu_{1m}(0) \rightarrow \nu_1$
$\nu_{2m}(0) \rightarrow \nu_2$

Final state: $\nu(f) = \cos\theta_m^0\, \nu_1 + \sin\theta_m^0\, \nu_2\, e^{i\phi}$

Probability to find ν_e averaged over oscillations

$$P_{ee} = |\langle\nu_e|\nu(f)\rangle|^2 = (\cos\theta \cos\theta_m^0)^2 + (\sin\theta \sin\theta_m^0)^2$$

$$= 0.5[\, 1 + \cos 2\theta_m^0 \cos 2\theta \,]$$

or

$$P_{ee} = \sin^2\theta + \cos 2\theta \cos^2\theta_m^0$$

New physics

$H = H_{st} + H_{np}$ in most of the cases

Decoherence - density matrix

More neutrino states: steriles, anti-nu

Classification:

Modification of the potential

Decoherence
Inelastic collisions
absorption

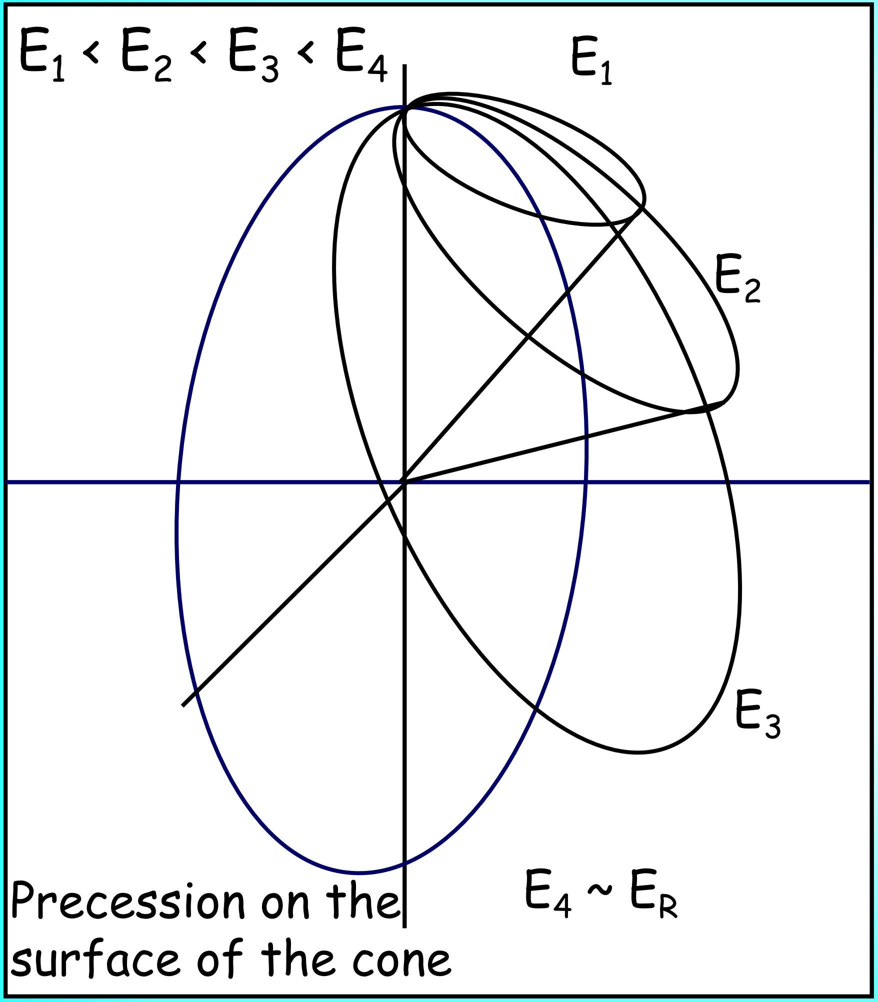
Signatures:

Spectra distortions
Time dependence
Appearance of antineutrinos

Previous bound, essentially: $H_{NP} < H_{st}$

Now $H_{NP} \ll H_{st}$

Resonance enhancement



Adiabatic conversion